

LOW FRICTION HULL COATINGS FOR ICEBREAKERS



PHASE II, PARTS I AND II

TECHNICAL REPORT

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Prepared for

**DEPARTMENT OF TRANSPORTATION
UNITED STATES COAST GUARD**

**Office of Research and Development
Washington, D.C. 20590**

1. Report No. 18 USCG-D-32-76 19	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle 6 Low Friction Hull Coating for Icebreakers, Phase II, Part I and II, Laboratory and Field Tests.	5. Report Date 11 February 1976	6. Performing Organization Code
7. Author(s) 10 S.J. Calabrese, M.B. Peterson & F.F. Ling	8. Performing Organization Report No.	9. Contract or Grant No. 15 DGT-CG-248634-A
9. Performing Organization Name and Address Rensselaer Polytechnic Institute Troy, New York 12181	10. Work Unit No. (TRAIS) 751341	11. Type of Report and Period Covered Phase II Technical Report 6-74 to 10-75 9 Jun 74-Oct 75
12. Sponsoring Agency Name and Address Commandant (G-DST-1/62 400 7th St., S.W. Washington, D.C. 20590 12 98 p.	13. Sponsoring Agency Code	14. Sponsoring Agency Code
15. Supplementary Notes This report documents Parts I and II of Phase II of the Low Friction Hull Coatings for Icebreakers project. Phase I report number is CG-D-107-74. Part III of Phase II is a separate report, number CG-D-33-76.		
16. Abstract Part I of Phase II involved a laboratory evaluation of coatings. Simulation tests were conducted to determine the effect of velocity, humidity, temperature, coating thickness, and contact area on ice friction. From these results, the friction resistance of the hull of an icebreaker was theorized. New materials were also evaluated for possible future use as coatings; and a study of the coating application procedure was conducted. Part II of Phase II was full-scale evaluation of coatings applied to small icebreakers. This was a continuation of testing done in Part II of Phase I. A solventless polyurethane was found to be a good icebreaker hull coating. Part III - under separate cover; is an analysis of icebreaking in particulate (slush) ice. ↑		
17. Key Words Ice Icebreaker Friction	18. Distribution Statement Document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.	
19. Security Classif. (of this report) UNCLASSIFIED	20. Security Classif. (of this page) UNCLASSIFIED	

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LOW FRICTION HULL COATINGS FOR ICEBREAKERS

PHASE II

PART I - LABORATORY INVESTIGATIONS OF COATINGS FOR ICEBREAKERS

PART II - FULL-SCALE TESTING

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Prepared for

U.S. Coast Guard Contract #DOT-CG-24634-A

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ACKNOWLEDGEMENT

The authors acknowledge the support given by Arctec Inc. of Columbia, Maryland and Miss Mary Ellen Haahr (RPI) and Mr. Leon Maday (RPI) for their contribution to the experimental effort.

$$J(\mathbf{z}) = \frac{1}{2} \mathbf{z}^T \mathbf{A} \mathbf{z} + \mathbf{b}^T \mathbf{z} + c, \quad \mathbf{z} = (z_1, \dots, z_n)^T, \quad \mathbf{A} = (a_{ij})_{i,j=1}^n, \quad \mathbf{b} = (b_1, \dots, b_n)^T, \quad c \in \mathbb{R}.$$

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The work reported herein was accomplished for the U.S. Coast Guard's Office of Research and Development, Marine Safety Technology Division, as part of its program in Ice Transportation Technology.

The contents of this report reflect the views of Rensselaer Polytechnic Institute, Troy, New York, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policy of the Coast Guard. This report does not constitute a standard, specification or regulation.

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SECTION 1

SUMMARY OF PROGRAM

This program was divided into three parts. Part I pertains to a laboratory study of properties of icebreaker hull coatings. Part II pertains to full-scale testing of candidate coatings on icebreakers. Part III is addressed to an analytical study on mush (particulate) ice.

1.1 Part I - Laboratory Investigation Rationale for Study Approach

Previous experience has shown that the coating on the bow of the hull of an icebreaker is removed first during icebreaking. The next portion to show damage or wear is at the ice line from the bow to midship. As the ship continues to break ice the damaged area increases until all of the coating is removed at the upper part of the hull. The maximum wear of an icebreaker coating is at the bow and usually at the upper portion of the stem. As it breaks hard ice the bow slides on the surface of the ice until the weight of the ship becomes greater than the strength of the ice. The ice then crushes and the bow drops back into the water.

Since this program is concerned mainly with the hull coating it was decided to concentrate effort by simulating the coating condition at the bow. If the coating remained on the bow it was assumed that it would remain on the lower portion of the hull. Also, it was felt that friction forces were dominant in the bow, and reducing these forces might significantly affect ice-breaking resistance.

The temperature of the ice varies from approximately 32° (0°C) near the water to near ambient air temperature at the surface. The temperature of the water below the ice can vary from 35°F to 40°F, depending on the time of the

year. The temperature of a layer of air between the ice and the water varies between the water temperature and the ice temperature.

The air temperature above the ice can be as low as -30°F (-34°C). Therefore the ice surface temperature can be very close to -30°F .

Figure I-4 shows the effect of temperature on the friction coefficient of steel sliding against ice. The friction values are close to leveling off at values below -10°C ($+14^{\circ}\text{F}$). Essentially the breakaway static and kinetic coefficient of friction appears to be constant at temperatures below -10°C . Therefore the temperature selected for this investigation is below -10°C .

There are some limitations in the application of the above rationale since the hull temperature and the temperature below the water is significantly above -10°C . During icebreaking some ice is pushed below the ship and travels along its length until the hull passes the submerged ice. This study does not specifically address itself to this portion of icebreaking since it is not yet known how much of the area of the ship is in contact under water and the coating wears at a much lower rate near the bottom of the hull. However, the theoretical and laboratory results of this study have application in both places.

The effect of load was shown during the Phase I portion of this program (Ref.2). The graphs plotted on page 51 of that report show the static and kinetic friction to be constant at loads from 50 lbs (32 psi) to 200 lbs (130 psi). Therefore the loads used throughout this evaluation will be above 50 lbs unless the effect of load is being studied.

Previous investigations on the frictional properties of materials sliding against ice included:

- (a) Effect of load
- (b) Effect of surface roughness
- (c) Effect of temperature

- (d) Effect of ice conditions
- (e) Effect of time in contact.

During this portion of the investigation, other parameters were studied.

They are:

- (a) Effect of velocity
- (b) Effect of humidity
- (c) Effect of coating thickness
- (d) Effect of surface area.

A synopsis of ice friction as it relates to icebreaking was theorized using the data obtained during the laboratory evaluation. Past effort has shown that the friction does play an important role in the overall resistance of a ship. The portion of resistance due to hull friction during icebreaking is not well defined. Some estimates are as high as 60%. Therefore the mechanism of ice friction was theorized.

The addition of new and exotic materials which can be applied to the hull of an icebreaker left many questions concerning the coating properties when applied under less than ideal conditions. The particular question was: can the application of an exotic material applied and cured under dry dock conditions produce comparable properties to the same coating if applied under near optimum conditions? A study of the problem was undertaken.

Many of the icebreakers in service have hulls containing large pits in the plates. The overall surface roughness of the hull is extremely high. Studies have shown that a reduction in resistance can be obtained by reducing the surface roughness of the hull (Refs.3,4). In order to reduce the surface roughness, several fillers were added to the primers of typical hull coating systems and applied to the surfaces of test specimens. An evaluation of the fillers and coating procedure was performed.

New materials which can be used to reduce the resistance on the hull are continuously appearing on the market. A continued search for other materials was conducted. One of the coatings which showed promise in this program is a nonsolvented system. Another system developed by Teknow-Maalitoy and Wartsila, Helsinki Shipyards, performed well during icebreaking. It is also a nonsolvented system (Refs.1,5). Therefore, emphasis was placed on an effort to find other nonsolvented systems which can be applied at a dry dock site.

1.2 Part II - Full-Scale Testing

During the Phase I (Ref.2) portion of this program, two icebreakers were coated with the candidate coatings and used for icebreaking. The results of that evaluation are discussed.

Other ships were coated and put into icebreaking service since the Phase I portion of the program. The results of that evaluation are also given. A list of the ships and coatings used are as follows:

Ship USCGC	Coating System	Coating Mfg.	Year Coated	Results
Yankton	Polyurethane elastomer	Goodyear	1973	Poor adhesion
Yankton	Polyurethane elastomer	Goodyear	1974	Poor adhesion
Sauk	Polyphenylene oxide	RPI	1973	Poor adhesion
Sauk	Polyurethane rigid	Dexter	1973	Good
Sauk	Bituminous epoxy	International Red Hand Paint Co.	1974	Pending
Raritan	Polyurethane nonsolvented	Xenex	1974	Very good
Mackinaw	Polyurethane, port side elastomer	Hughson	1974	Poor
	stbd.side rigid	Hughson	1974	Fair
Mackinaw	Polyurethane nonsolvented	Xenex	1975	Pending
North Wind	Polyurethane rigid	Hughson	1975	Pending
West Wind	Glass flake polyester	Baltimore Copper Paint	1974	Fair

1.3 Part III - Analysis of Icebreaking in Mush Ice

Mush ice was said to be one of the most difficult types of ice coverage to navigate through. It is very difficult to test in mush ice since it does not support a load except through buoyant forces. Little is known about the properties of mush ice concerning its shear strength, compacting characteristics and adhesive properties. An analytical study of mush ice was performed. The results of this study entitled "Analysis of Icebreaking in Particulate Ice" by H.J. Sneek and J.M. Kaufman are reported under separate cover.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

1. The coefficient of friction of materials sliding against ice changes with the velocity at low speeds and then will level off and remain constant. The speed at which the friction levels off, is dependent on the surface roughness and type of material. The values start at the static value and gradually decrease to the kinetic value as the speed increases. The slope of the decrease changes with the surface roughness. This same trend was seen when sliding steel surfaces against ice as well as surfaces coated with various plastics.
2. The coefficient of friction does not appear to change significantly with the ice roughness. The only change is noted at very low speeds and is attributed to surface wringing.
3. The low speed friction coefficient varies significantly with relative humidity but is less significant at higher speed. The reason attributed is the moisture condensing on the ice surface forming a film between the slider and the ice. At higher speed the frictional heat provides water at the surface and therefore less effect of moisture is noted.
4. Coef. of friction appears to be dependent on the pressure of contact. Larger areas produce a higher friction coefficient when sliding on ice than smaller areas under the same load. This was noted on hard ice with a larger surface under heavy load. Similar tests run on the same

geometry, 1/10 scale model and on soft ice did not produce the same results because the ice was at higher temperatures and therefore softer. It is recommended that a similar test be run using 1/10 scale model on hard ice to attempt to reproduce the full-scale tests.

5. No significant difference was noted in the friction coefficient of different thickness of epoxy coating sliding against ice. It is felt that this applies to other coating materials which are hard at the sliding temperature.
6. Based on laboratory friction and wear test data, several new potential icebreaker coatings were found. They are:
 - (a) unfilled, nonsolvented, polyurethane (Zebron)
 - (b) nonsolvented epoxy (Inerta 160)
 - (c) epoxy W2 (Woolsey Marine).

The nonsolvented polyurethane (unfilled) gave promising results during the wear and friction tests. It is recommended that a portion of a hull be coated with the nonsolvented unfilled polyurethane while the rest of the hull is coated with the normal filled nonsolvented polyurethane (see paragraphs 21 and 22 below). Complete evaluation was not performed on the nonsolvented epoxy due to delays in obtaining the material. It is recommended that the testing be continued on this material to determine its frictional properties against ice and its bond strength values.

The W2 epoxy gave promising results during the bench testing; but to the authors' knowledge, it is not yet available for commercial application. Little data is available concerning its application parameter and curing characteristics.

7. Environmental conditions during coating application appear to affect some coatings more than others. Little difference in bond strength

was noted when curing epoxy coating systems under outdoor or indoor conditions. When curing polyurethane coatings, however, an increase in bond strength was noted when the coating was cured indoors. It is recommended that similar tests be run under different temperature and humidity conditions to determine if the above trend continues. It is especially important that a similar study be conducted on the nonsolvented polyurethane to determine the optimum coating conditions for maximum bond strength.

8. The choice of solvents used as cleaning agents affects bond strength of the applied coating. A significant reduction in bond strength was noted when cleaning the surface of an epoxy coating before applying subsequent coats. The cleaning solvent was toluene. Similar tests should be run using other solvents as cleaning agents. Periodically, it becomes necessary to clean or reactivate a hull surface which has become contaminated. It is important to determine the effect that the solvent has on the coating properties.
9. A significant reduction in surface roughness can be achieved by adding colloidal silica to the primer of a coating system. The coating can be sprayed on a ships hull and immediately squeegeed while wet. This fills the pits or pores leaving a smoother surface to apply subsequent topcoats.
10. A model for the frictional behavior of ice has been proposed. Two regimes have been identified. At pressures less than 100 psi, friction coefficient is constant, and the frictional shear force is a function of the normal force. At pressures greater than 100 psi, the friction coefficient decreases with pressure, however the frictional shear strength at the interface is constant. In the high pressure region

there are friction contributions from both interface slip and surface deformation around the asperities. Based upon the results which have been obtained, a technique is proposed which predicts hull friction from bench tests run at 100 psi. To predict friction in service the hull roughness, velocity, temperature, and contact area must be known.

11. Solvented elastomeric coatings such as the Goodyear and Hughson elastomeric produced poor results on the underwater hull of an icebreaker. This is regardless of the type of curing system (moisture cure, chemical cure). It could be that solvented elastomer systems are more susceptible to hydrolysis.
 12. The solvented rigid polyurethane coatings gave fair to good results in all areas except where maximum wear occurs (bow area near the water line). The highest bond strength value obtained on the rigid urethane was 988 psi and it did not survive icebreaking service.
 13. Based on the results of the USCG Cutter Raritan evaluation, the most promising material tested was a nonsolvented polyurethane. It gave bond strength values of approximately 1500 psi. The maximum damage seen was at the bow stem and on several 1 sq.ft. areas near the bow. Up to this point, none of the materials tested remained on the surface near the water line. The nonsolvented urethane remained on most of the water line and produced the highest bond strength values of any coatings evaluated. It becomes evident that the bond strength values needed to maintain the coating should be at least 1500 psi. This is a significant fact since prior to this effort the bond strength values needed for icebreaking service were unknown.
- Successful results on nonsolvented coatings were also found during full-scale testing on icebreakers built in Finland (Icebreaker Silma and Valpas). In this instance the icebreaker coating used was a

nonsolvent epoxy and it performed well during service.

A study, to understand the bonding mechanism of the solvent and non-solvent coatings, should be undertaken. The purpose would be to identify the principal reason for the difference in bonding mechanisms.

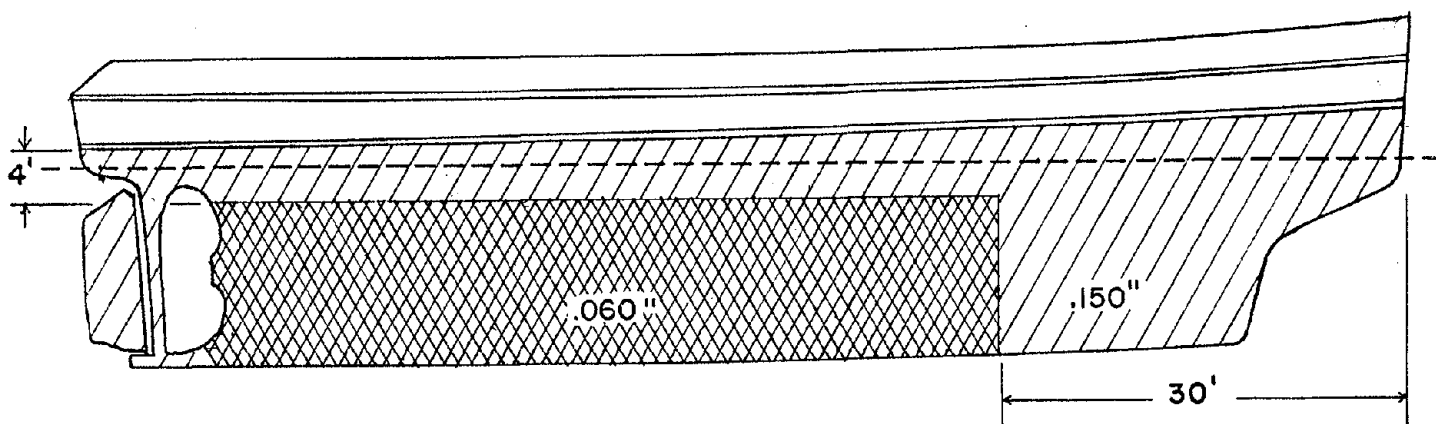
14. Some indication of a reduction in hull resistance was seen with the nonsolvent urethane. A closer examination of this phenomenon by instrumenting the ship's hull before and after coating should be undertaken.
15. Low friction coatings provide low adhesion to fouling matter. In all cases (salt and fresh water) marine growth was removed from the polyurethane coating after service by washing with water. A study to determine the antifouling characteristics of this type of system should be undertaken. If the marine growth on the hull can be periodically removed without destroying the coating it could mean a significant maintenance cost savings.
16. The surface roughness of a heavily pitted hull (USCG Mackinaw) was drastically reduced by spraying a high viscosity coating system and immediately squeegeeing the top layer off, thereby filling the pits. Subsequent coats were applied to obtain the desired final thickness.
17. The hull of the USCG Cutter Polar Star will be coated soon. Based on results to date, it is recommended that the nonsolvent polyurethane be applied to the hull. Since the ship is the largest of the Coast Guard icebreakers, it may be very expensive to coat the entire hull. A study should be undertaken which would include the coating of various portions of the hull of an icebreaker with friction materials to determine if the entire hull should be coated with the nonsolvent polyurethane. This could be accomplished by utilizing model testing techniques and

measuring the total resistance of the ship passing through an ice tank. A single ice thickness should be used and various parts of the hull should be coated with a low friction coating.

It may be found that the portion of the ship which contributes the maximum resistance is the ice line and the bottom portion need only be coated for corrosion and antifoul protection. This would mean a significant reduction in cost for coating the USCG Cutter Polar Star. This data could also be used for other large icebreakers, reducing the coating costs as well as reducing the hull resistance.

18. The hull coating on an icebreaker shows the maximum wear at a bow and water line indicating maximum abrasion. However, the coating beneath the water line is also worn down. The broken ice passes underneath the hull and is in contact with the ship for a period of time. It is important to determine the amount and size of the ice pieces which slide against the hull during icebreaking. This cannot be positively determined by model testing since the ice characteristics are not the same as that seen in full-scale tests. It is recommended that a photographic survey be undertaken to determine the ice path during icebreaking. This could be accomplished by placing a movie camera and TV camera on a boom beneath the water surface and observing a ship as it passes through an ice field. Preliminary data on available light, exposure and lens / hull distance will need to be obtained before the observation task can be performed. All observation equipment can be placed on a second ship while observing the icebreaking process. The boom direction can be controlled by observing a TV monitor on the equipment ship and adjusting the boom for maximum observation.

19. A 110 ft icebreaking tug, which would see service in salt water ice should be coated with the nonsolvented polyurethane. This ship should contain a portion of the hull with the unfilled nonsolvented polyurethane coating to be used as a direct comparison to the filled coating. The task can be combined with that discussed in paragraph 20 below.
20. The hulls of three icebreaking tugs (110 ft WYTM) were coated with polyurethane coatings and periodically examined. The results of the examination show that the nonsolvented polyurethane performed best in fresh water. A definite pattern of wear was noted on this hull design. The highest wear area is at the bow near the water line. The water line from the bow to midship gave the second greatest area of wear and surface damage. The rudder and stern are the third areas of wear. It is recommended that a WYTM operating in salt water be coated with the nonsolvented polyurethane system. The coating should be applied as shown in the following sketch.



SECTION 3

INTRODUCTION

High frictional resistance of ice against the hulls of icebreakers is a problem which has existed for many years. Because of this, higher power is required than would otherwise be necessary. Even more serious, icebreakers and other vessels can become "stuck" in ice fields and considerable effort must be expended to free them. Any means to reduce the friction between the ice and the hull would be highly desirable. Several means have been proposed to reduce the friction and abrasion of ice either by improved design of the hull or by auxiliary devices. These have in several instances proved to be successful. They are, however, costly to install and maintain. A simpler approach would be to develop a coating which would give lower friction against ice than the steel hull. To this end a program was initiated by the U.S. Coast Guard at RPI under Contract No. DOT-CG-24634-A. The objectives of this program were to develop and evaluate potential materials as low friction coating materials for icebreakers. Hull maintenance is an equally important objective, since the coating at the bow and the water line is removed within a short time period of icebreaking service and continued coating wear is noted throughout the icebreaking season. The ship must be recoated on a minimum of two-year cycle but this is shortened to one year if the ship is put into dry dock for other maintenance purposes. In carrying out this investigation, it was almost immediately apparent that many ice friction reducing coatings existed. The real problem was to make them sufficiently abrasion resistant and adherent. This then became a major focus of the program.

Full-scale testing has been done on Finnish icebreakers during the period between 1972 and the present (Ref.1). The icebreakers used were the Silma and the Valpas. Figure I-1 shows the results of the tests. The Silma is an older ship (seven years) and the hull contained several pits. The Valpas is only two years old and the hull was much smoother. Both ships were tested in similar ice in 1972. The plot of speed vs. resistance obtained during the 1972 run is shown in Figure I-1. The Silma then was coated with a nonsolvented epoxy (Inerta 160) manufactured in Finland. The ships were again tested in ice in 1974. The results (Fig.I-1) show a significant reduction in resistance for the Silma (coated hull) and an increase in resistance for the Valpas.

Other data taken from model tests at Arctec Inc. show a significant reduction in resistance as a function of speed with coatings of two friction factors on the hull (.3 and .1). The results of the model tests are shown in Figure I-2. The resistance at 1 knot is approximately 17 tons and increases to 24 tons at 4 knots when the hull friction coefficient is .3. If the friction coefficient is reduced to .1, the resistance at 1 knot is approximately 10 tons and increases to 15 tons at 4 knots.

Therefore, evidence from model tests and full-scale tests show a reduction in resistance during icebreaking can be obtained by applying a low friction coating to the hull of an icebreaker.

Phase I of the program (Ref.2) dealt with the initial screen test evaluation of available materials and the application of the most promising materials to the hull of an icebreaker.

Phase II of this program, described in this report, is divided into three parts: Part I is concerned with laboratory investigations, Part II deals with the results of ship's coating and Part III is an analytical study of frictional resistance in mush ice. These various investigations are described in more detail in the following section.

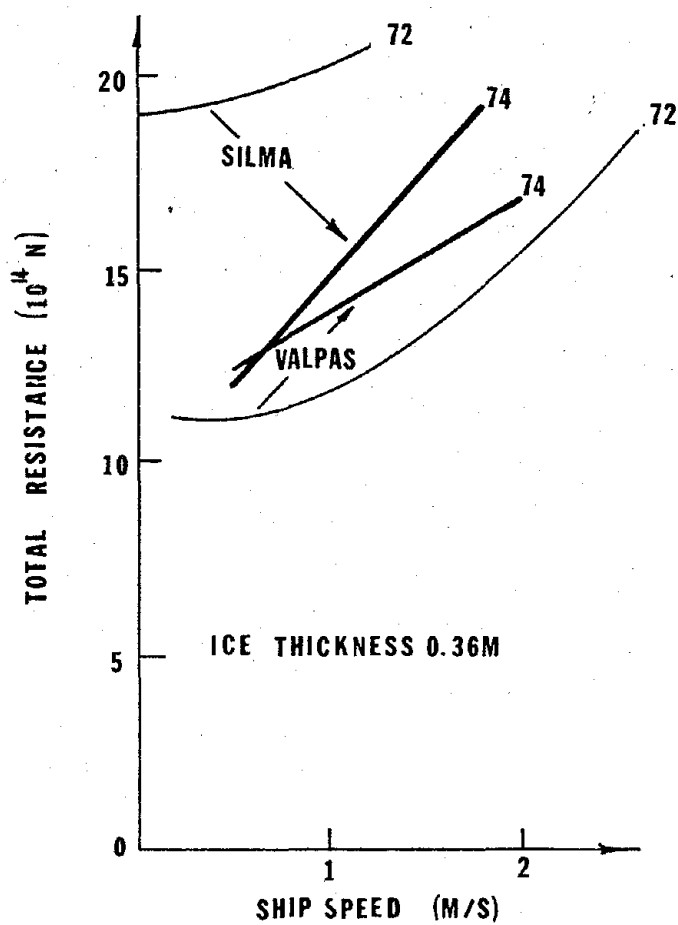


Figure I-1 Results of Full-Scale Testing of Two Finnish Icebreakers. Silma was coated with a non-solvented epoxy. Valpas was not.

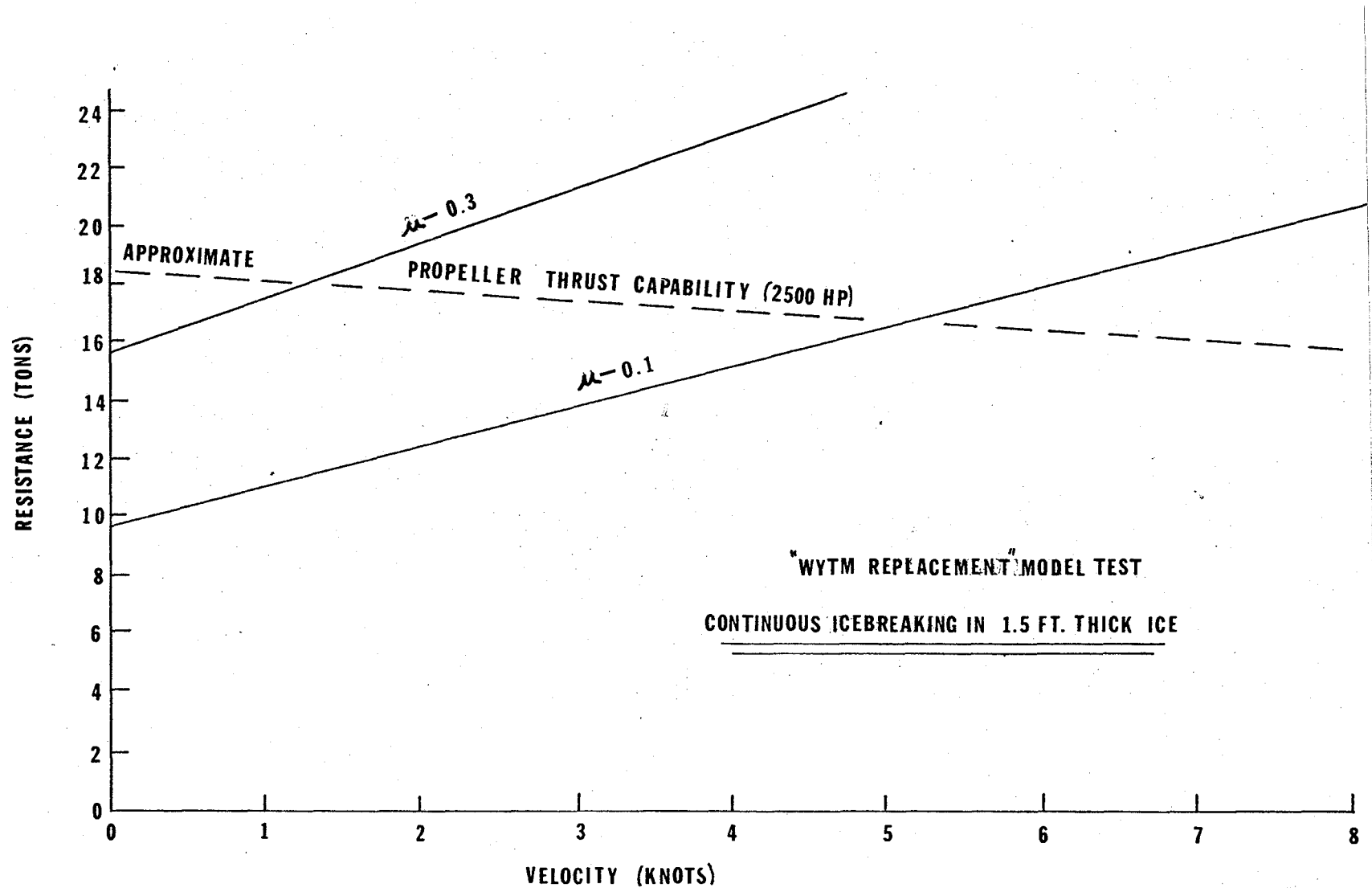


Figure I-2 Results of a Model Test Evaluation Showing a Single Hull Design Containing Coatings with Different Levels of Friction Coefficient against Ice. Evaluation was performed by Arctec, Inc.

PHASE II

PART I

LABORATORY INVESTIGATIONS OF COATINGS FOR ICEBREAKERS

SECTION 4

FRICTIONAL BEHAVIOR

Previous Results

In the previous report (2) a review of the literature was published and an experimental investigation was conducted to determine the effects of certain variables. Under the conditions of those tests it was found that the friction was a function of the strength of the ice and varied significantly with temperature, roughness, and time in contact. The condition of the ice (snow, rough, etc.), load, and velocity did not appear to affect frictional behavior except that static friction was much higher than kinetic friction. No correlation could be found between contact angle of water on various materials and frictional behavior, and material "scratch" hardness and frictional behavior.

Static friction increased with time in contact and, for rough steel surfaces, varied between a maximum of 1.2 (called breakaway) and 0.80 (called static). Kinetic friction was considered to be an extension of the time in contact concept.

Static friction also varied significantly with surface roughness for steel, increasing from 0.40 (breakaway) to 1.2 as the roughness increased from 20 CLA to 240 CLA. Kinetic friction increased only slightly (0.09 to 0.11). A plot of the static friction versus roughness for a variety of materials is shown in Figure I-3. It can be seen that the friction increases with roughness for all materials. The increase is considerably lower for materials such as Teflon (PTFE) or Polyethylene (PE).

The friction data showing the effect of temperature from Ref.2 is shown in Figure I-4. Static friction is high at low temperatures and begins to decrease at a temperature of -7°C ($+22^{\circ}\text{F}$) where the strength of the ice drops considerably. For smooth surfaces friction values decrease to those found

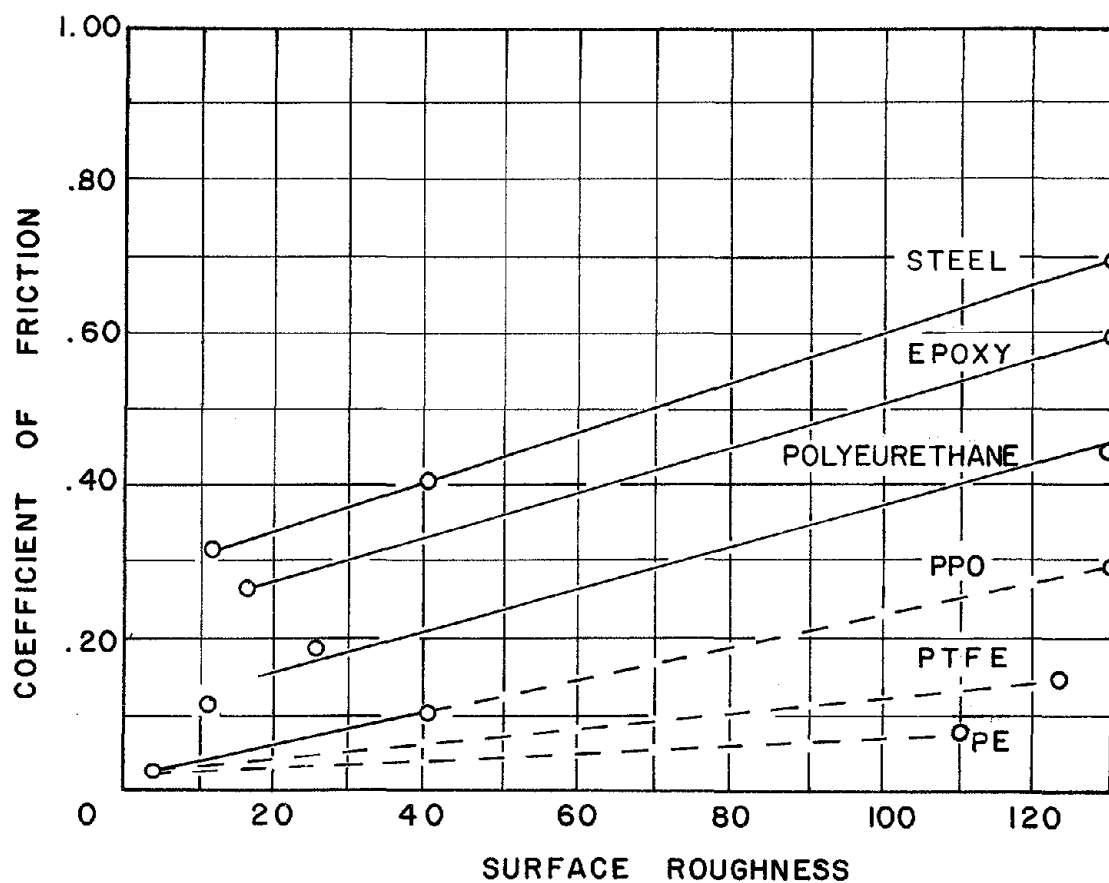


Figure I-3 Effect of Surface Roughness on the Coefficient of Static Friction for Several Different Materials. Load 200#, Temp. -7°C (-22°F)

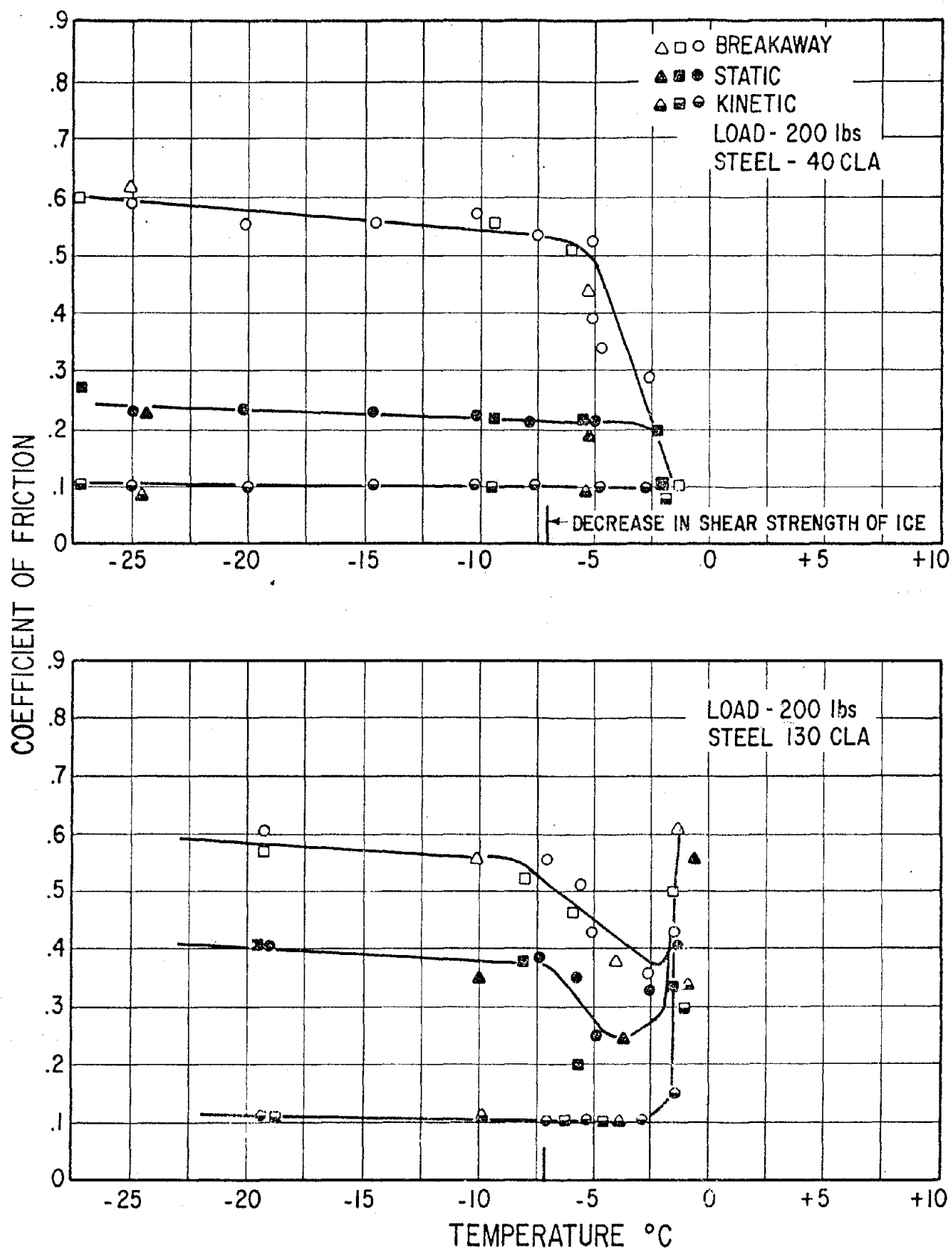


Figure I-4 Effect of Temperature on the Coefficient of Friction of Steel of Various Surface Roughness Sliding Against Solid Ice

for kinetic friction; however, for rough surfaces a large increase was noted in the vicinity of 0°C (+32°F). No conclusive explanation was given for this phenomenon. More data is needed in this temperature range to study the effect.

Efforts were initiated to understand the role of material properties on frictional behavior. It is clear from Figure I-3 and common knowledge that different materials give different frictional behavior, independent of roughness. The question to be answered is whether it is strictly a surface adhesion effect or whether the hardness of the material plays a significant role. A replot of the data of Figure 27, Ref.2, is shown in Figure I-5.

This data is for a single polyurethane compounded to yield different hardness levels (surface roughness is 35 μ " CLA). It is clear from these data that lower friction results when the harder materials are used. It is not clear, however, what would happen if the data could be obtained at lower hardness levels with the same material. With softer materials, friction may increase since the ice could penetrate the material. This effect was, in fact, found; that is, certain low adhesion materials gave high friction. Examination of the surface after the test with a surface profilometer indicated that it was quite rough. After several hours, however, this roughness disappeared. On the other hand, softer surfaces which are rough were found to give lower friction. This could also be attributed to the fact that they were unable to penetrate the ice (Figure I-3). Thus it was concluded that it is extremely difficult to separate the effects of roughness, hardness and adhesion and to determine their independent effects on friction.

In order to arrive at a more precise mechanism of ice friction some further experiments were performed. These experiments were primarily directed at relating the previous data to hull friction.

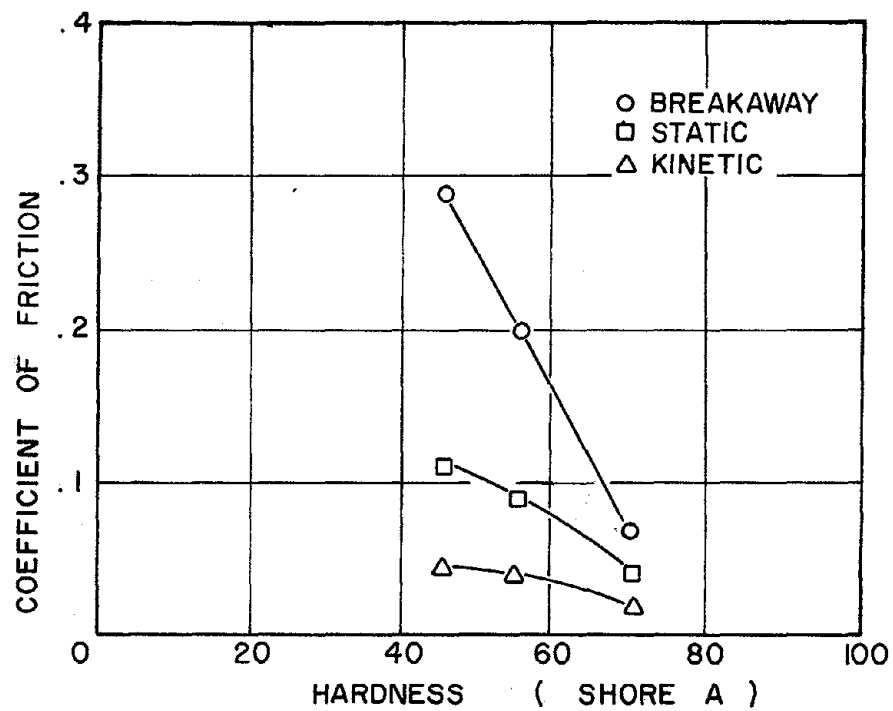


Figure I-5 Effect of Hardness on the Coefficient of Friction of Polyurethane Sliding Against Ice. Load 200#, Temp. -4°C (25°F)

4.1 Effect of Velocity

The velocity of a ship during icebreaking is usually as fast as the ship can travel through the ice safely. This usually varies between 6 mph and 12 mph depending on the ice condition. If the speed is reduced to under 3 mph, there is a fairly good chance that the ship will get bogged down and have to proceed under high power or ram.

The kinetic frictional values were reported .1 or lower for various materials sliding against ice at 283 ft/min (3 mph) (Ref.2). In this program further tests were run to determine friction characteristics at lower velocities.

The test rig used is described in the previous report. Figure I-6 shows an overall view of the test rig. The essential parts of the rig are:

- (a) A 2" OD \times 1 1/2" ID ring sliding against a flat plate of ice.
- (b) A ball and socket pivot holder which accepts the ring specimen.
- (c) A drive shaft held in a drill press which accepts the test specimen and housing.
- (d) A piece of ice frozen in a cup and mounted in a housing. The housing is held on angular contact ball bearings in an aluminum block below a seal.
- (e) Torque arms mounted on the side of the housing which strike strain-gaged flexure beams.

The test rig is mounted in a cold box, refrigerated by a tandem compression refrigeration unit. The refrigerating coils surround the test rig inside the cold box. The temperature is controlled with a thermocouple in the ice holder and measured with a second thermocouple imbedded in the ice holder.

The load is applied by placing dead weights on the drill press feed lever.

The drill press was modified by installing a 1 hp dc variable speed motor and a controller.

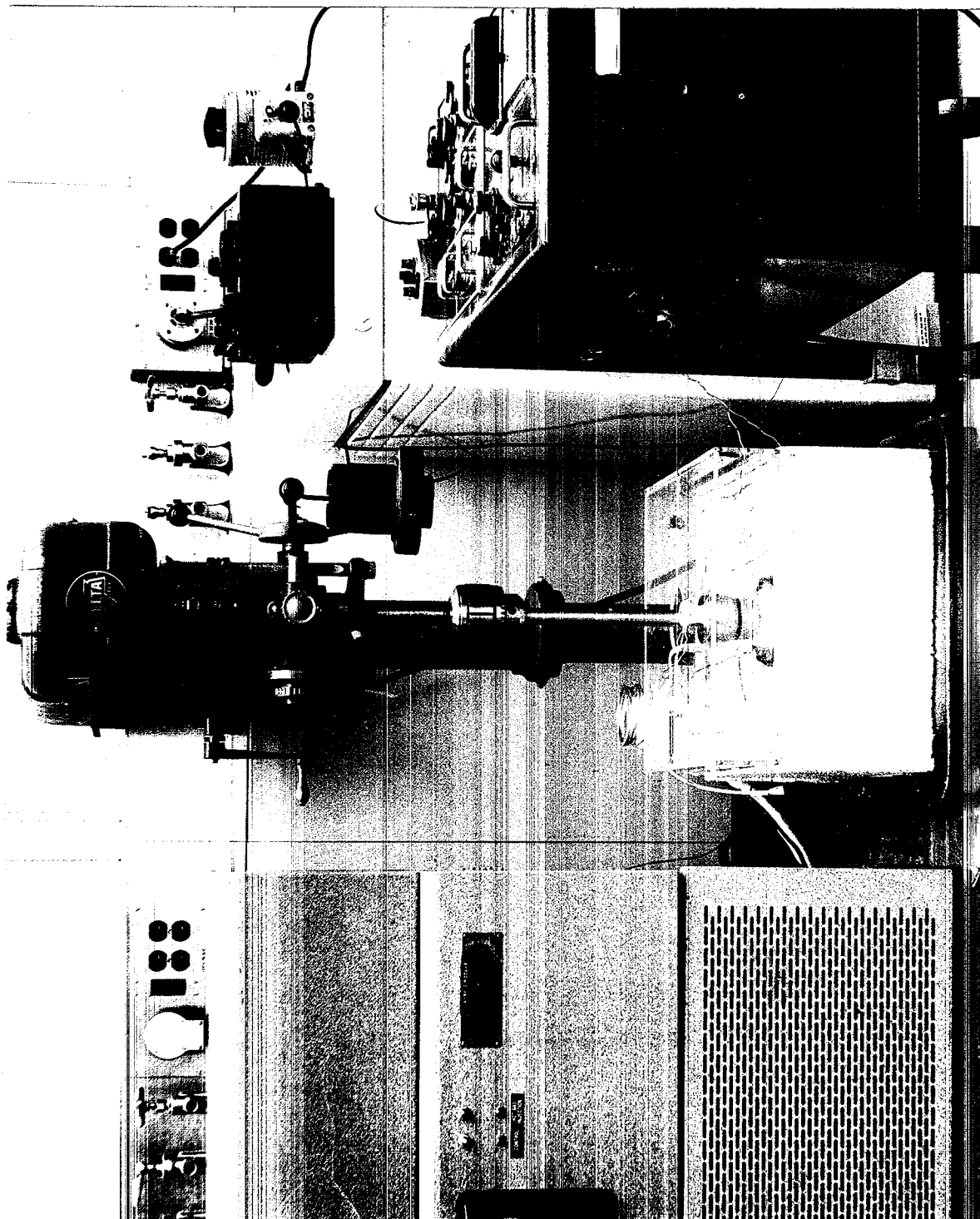


Figure I-6 Overall View of the Friction Test Rig

The tests were run under the following conditions:

- (a) Load - 80 lbs
- (b) Temperature - 18°C (-2°F)
- (c) Relative humidity - 2%
- (d) Ice condition - "as frozen"
- (e) Surface roughness - as indicated
- (f) Velocity - as indicated.

The test procedure was as follows:

- (a) Allow all surfaces to come to an equilibrium temperature.
- (b) Place test specimen in contact with the ice.
- (c) Rotate test specimen at low speed to measure static friction and increase to desired velocity.
- (d) Reduce speed and measure friction force continuously.
- (e) Repeat (c) and (d) for a total of 3 times.
- (f) At the end of the test cycle the specimen was rotated at a constant velocity for 1/2 hour and the torque was monitored continuously to determine if the friction remained constant during that period.

The results of the tests are shown in Figures I-7 through I-10.

Figure I-7 shows the velocity vs friction curve for steel at two surface roughnesses (100 μ " and 200 μ " CLA). Three tests are shown.

The 200 μ " CLA surface roughness test shows a gradual decrease in friction from .5 to .1. The .1 value is reached at approximately 1.5 miles/hr. Above 1.5 miles/hr the friction coefficient remains constant at .1.

The 100 μ " CLA surface roughness test shows a more rapid reduction in friction and appears to have leveled off at approximately .5 mph. The final friction coefficient was approximately .08 - .09. A comparison of the friction

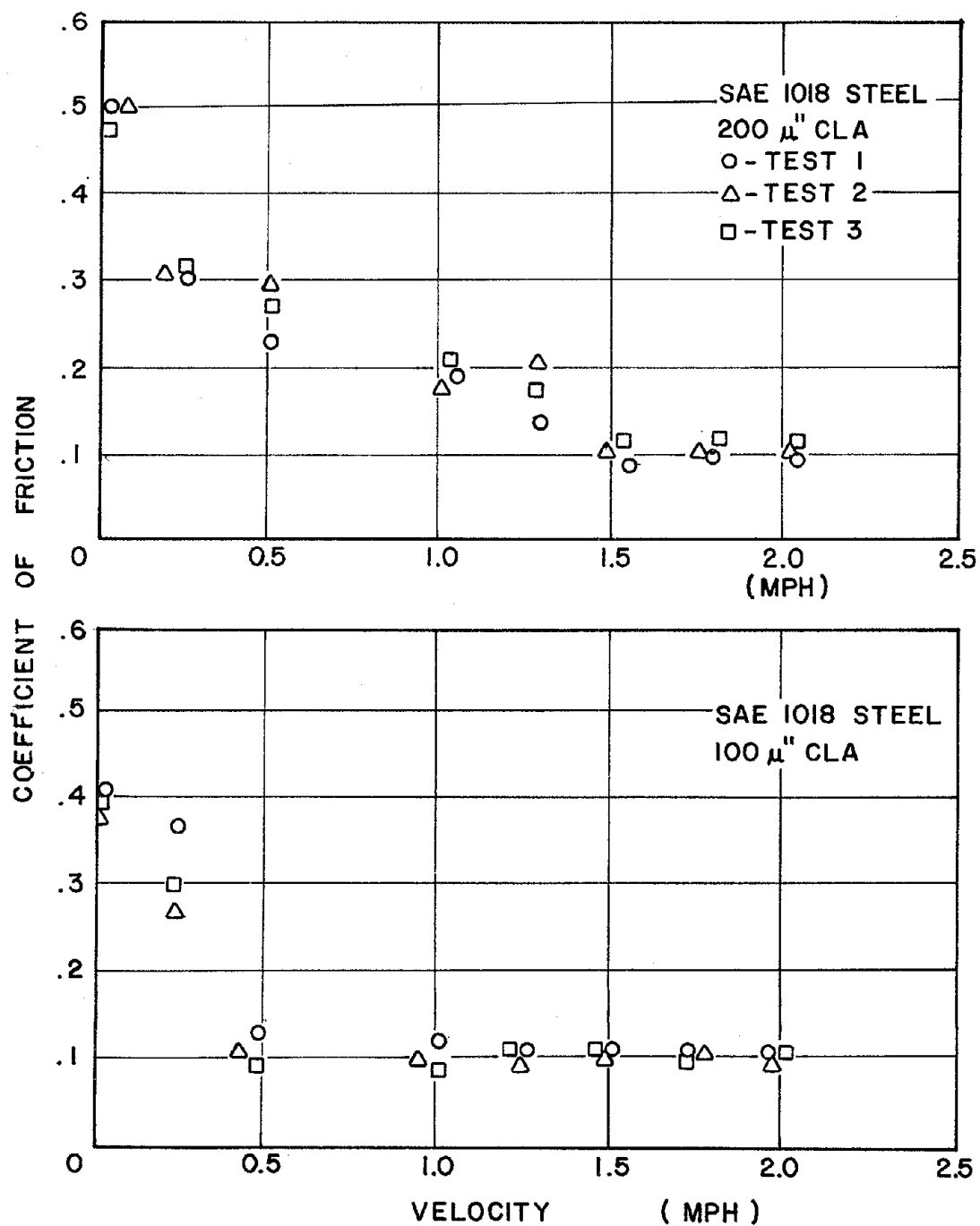


Figure I-7 Effect of Velocity on the Friction Coefficient of Steel Sliding Against Ice

coefficient at .5 mph shows the 200 μ " surface gave a friction coefficient .3 and the 100 μ " surface gave between .11 and .14.

Figures I-8 through I-10 show the results of the tests run on several materials. The materials evaluated were:

Polycarbonate

Nylon

Navy teflon #3

Glass

Acrylic

Solid teflon

Rigid polyurethane (chemical cure)

Rigid polyurethane (moisture cure)

Copolymer.

The tests were run on an "as frozen" surface and on an ice surface prepared by polishing. The normal surface roughness of the ice is in the "as frozen condition". Hence the ice roughness that an icebreaker is subjected to is in the "as frozen" condition. Past experience has shown that the surface roughness of the material sliding against ice can vary the friction coefficient significantly. The next question which is suggested is "does the surface roughness of the ice have an effect on the friction coefficient?" Therefore these tests were run on the "as frozen" surface and on a prepared ice surface. The surface roughness of the polished surface (smooth ice) was 10 μ ".

The test results for the coatings show the same trend as those run on steel. Slow speed friction levels are near the static values and higher speed at the kinetic values of friction previously measured.

The surface roughness of each material tested is shown in Figures I-8 - I-10.

ROUGH ICE

SMOOTH ICE

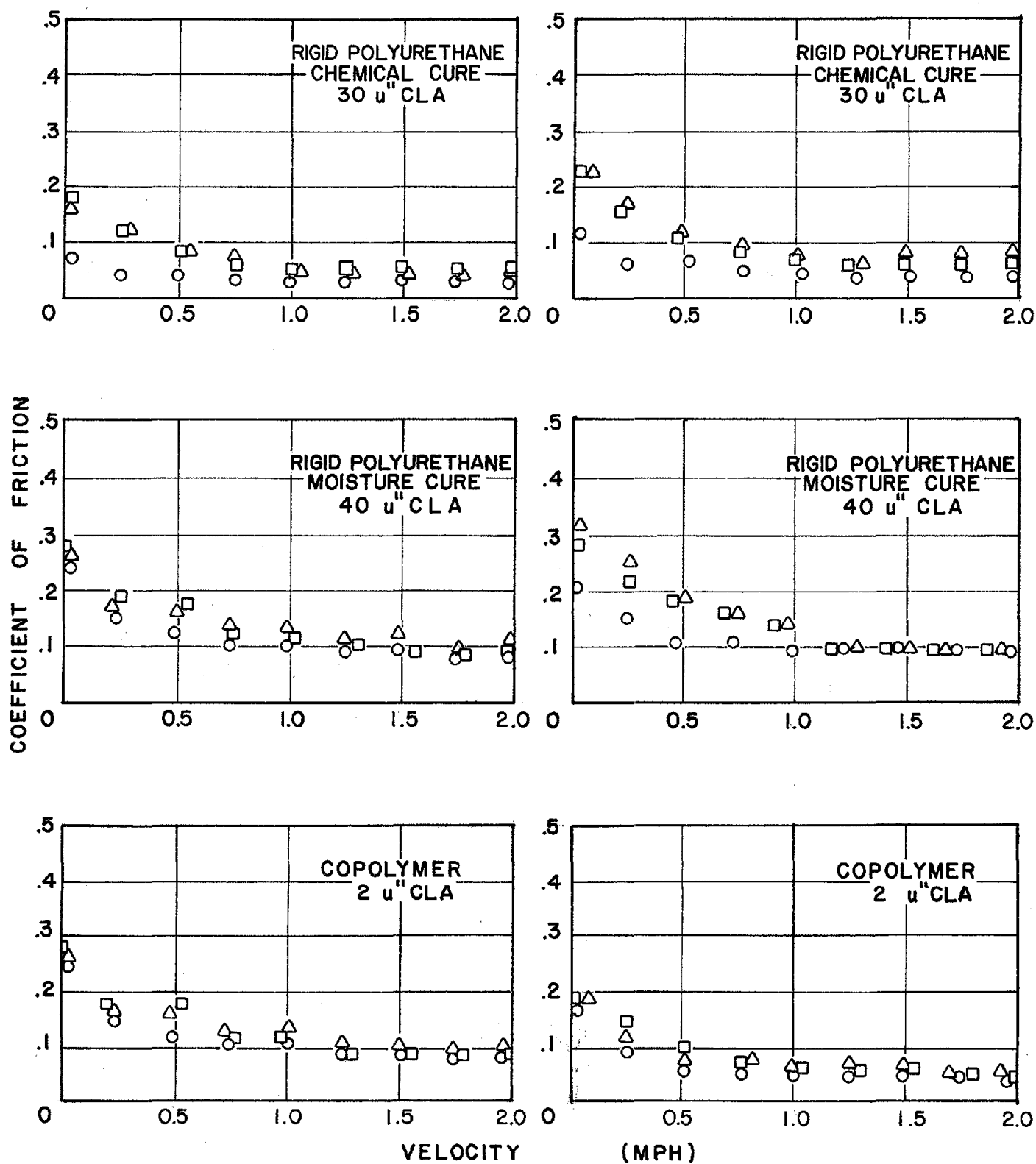


Figure I-8 Effect of Speed on the Coefficient of Friction of Various Materials Sliding Against Ice. Temp. -19°C (-2°F)

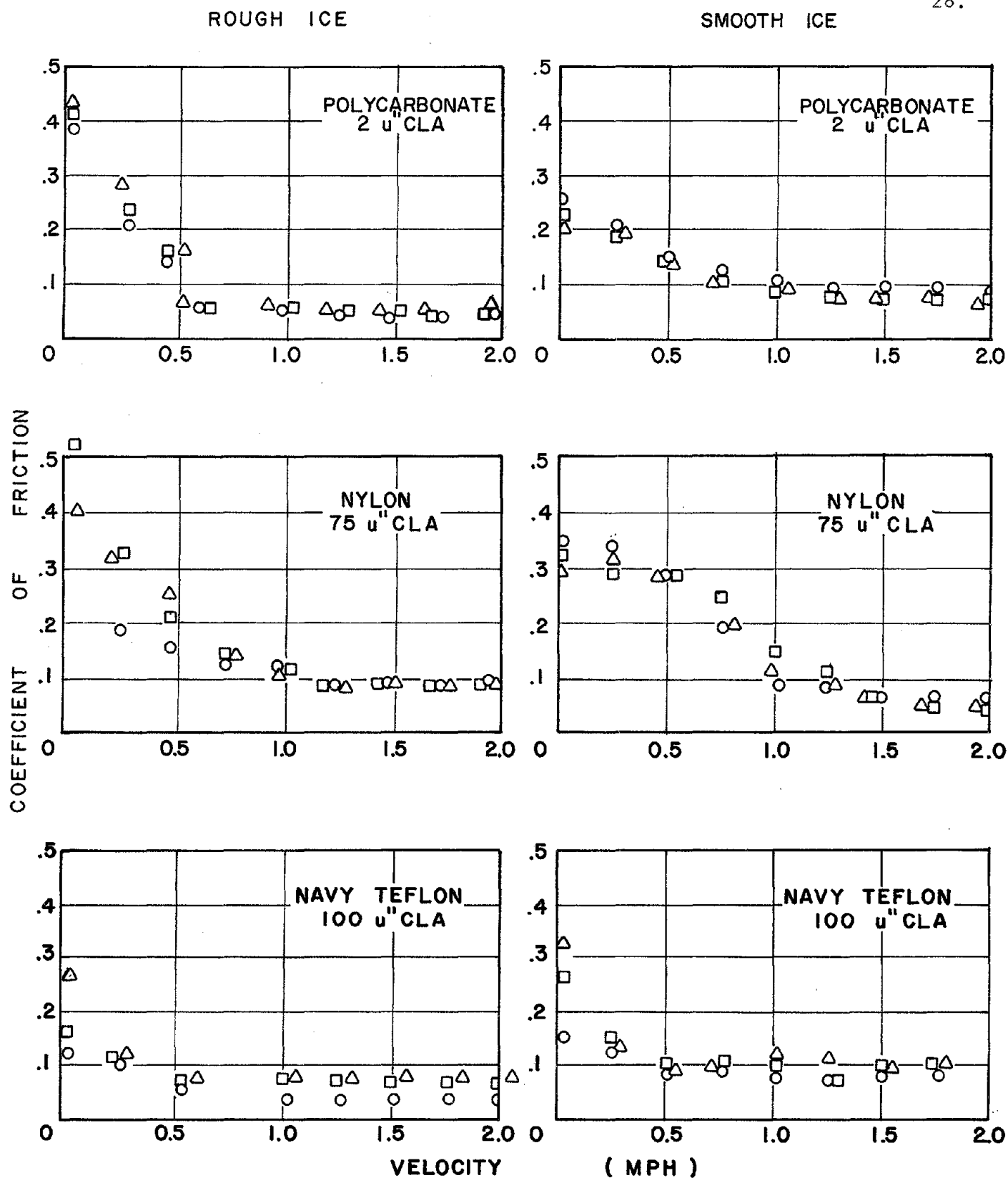


Figure I-9 Effect of Speed on the Coefficient of Friction of Various Materials Sliding Against Ice. Temp. -19°C (-2°F)

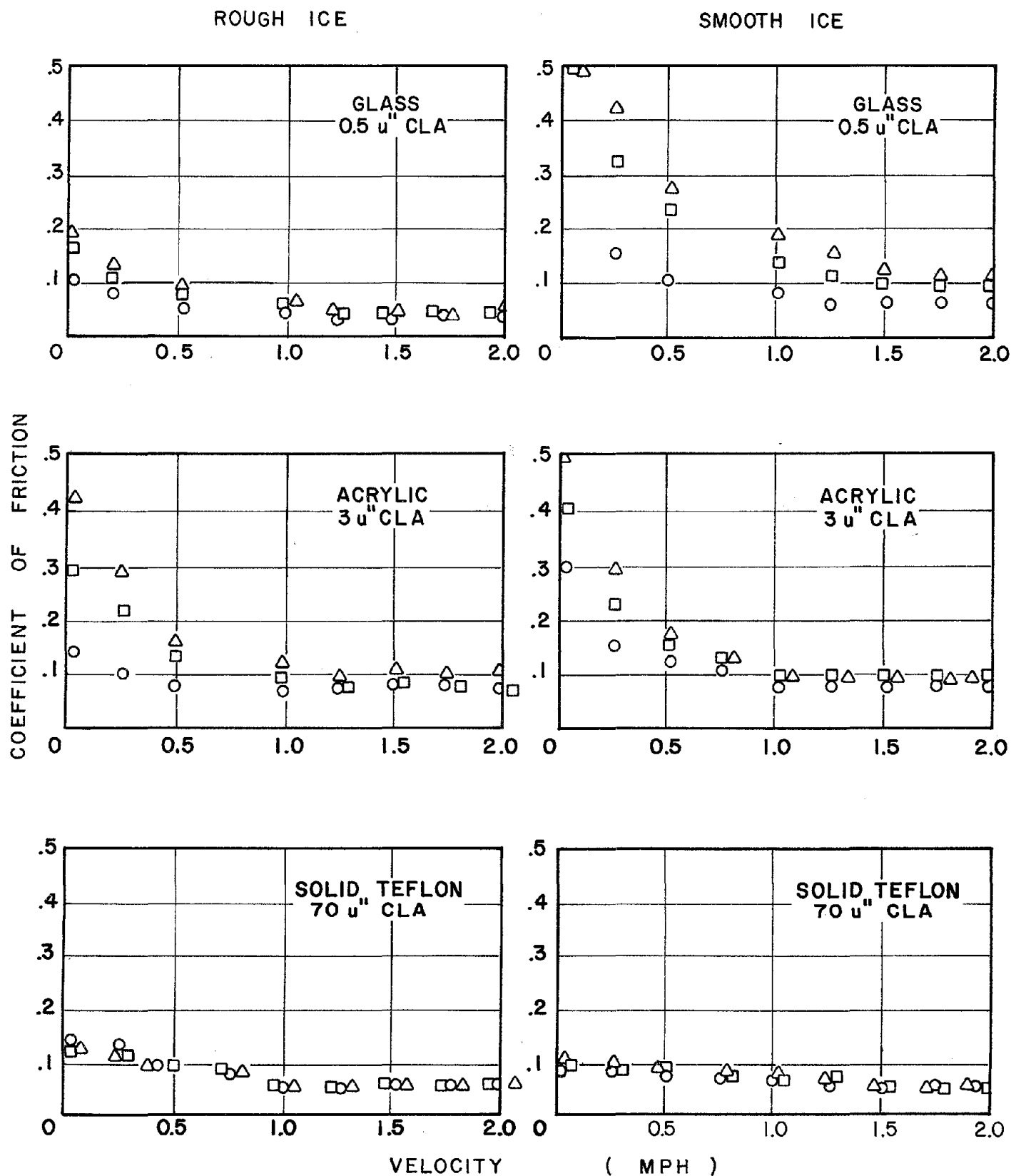


Figure I-10 Effect of Speed on the Coefficient of Friction of Various Materials Sliding Against Ice. Temp. -19°C (-2°F)

Only slight differences are seen when testing these materials against smooth or rough ice. The most significant difference seems to be with the glass. The test run on smooth glass vs smooth ice shows a considerable increase in friction over the smooth glass run on rough ice. The reason for this is possibly that both surfaces are so smooth that they tend to wring together.

A typical trace taken during the friction-velocity investigation is shown in Figure I-11. The velocity increased from right to the center of the trace and decreased from the center to the left side of the chart. The initial high friction is the "breakaway" friction discussed in the Phase I portion of the program. The second level of friction force is the static value which decreases to the kinetic value where it remains constant (start to center of the trace). As the speed decreases the friction force remains constant (center of the trace) and increases as the velocity decreases back to zero (center to right). The trace indicates a decrease in friction as the speed increases from zero to some velocity depending on the surface roughness and the material. It then levels off and remains constant regardless of the speed.

4.2 Effect of Humidity on the Frictional Behavior of Steel Sliding Against Ice

The ice surface that an icebreaker is subjected to depends on the temperature and humidity of the environment. It can be hard ice under a cover of snow or hard ice with condensed moisture on the surface from the increased relative humidity or hard ice with moisture on the surface from the sun's melting. Any combination of the above can exist, causing a difference in the ice surface from that which has been previously tested. Therefore, a series of tests was proposed to study the effect of relative humidity.

Previous data on the frictional behavior of ice has been run at a controlled relative humidity of less than 10%. This was done to keep the conditions constant during the materials investigation. The conditions for breaking

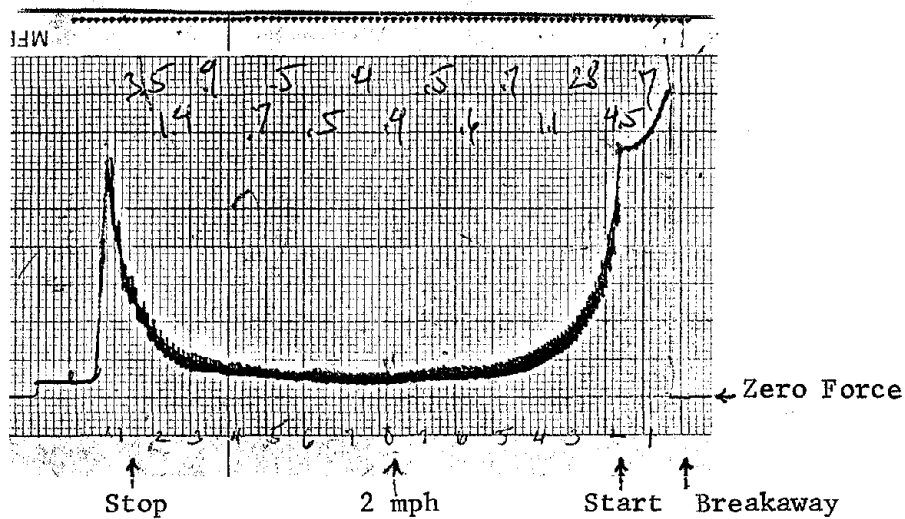


Figure I-11 Typical Trace Taken During the Effect of Speed Evaluation

ice are, of course, not controllable. Hence a study was conducted to determine the effect of humidity on the frictional behavior of ice. A series of tests were run to establish the effect on friction at several humidity levels.

The friction test rig was modified to control and measure the relative humidity. An air drying tower, a water reservoir and air source were installed to allow air, at a given moisture level, to pass into the test rig. A temperature and humidity probe were placed in the test chamber and read out on a Humidity/Temperature Indicator. Air was passed through the drying tower to remove all moisture and then bubbled through water to pick up moisture. The air was then passed through a coil placed in a freezing compartment to reduce the temperature and deposited into the test chamber. The air delivered to the test chamber contained excessive moisture for the temperature to which it was subjected thus causing condensation and frost build-up on the surface in the test rig. A minimum of one hour had to be allowed for temperature and humidity stabilization after the test conditions were reached. A schematic of the humidity control system is shown in Figure I-12.

The tests were run under the following conditions:

- A - temperature - -29°C (-20°F) and -18°C (0°F)
- B - humidity as indicated
- C - velocity - 0 to 2 mph
- D - load - as indicated
- E - surface roughness of slider - as indicated.

The test procedure was as follows:

- (a) Reduce rig temperature to the desired test temperature.
- (b) Set up the ice specimen and slider specimen in the rig.

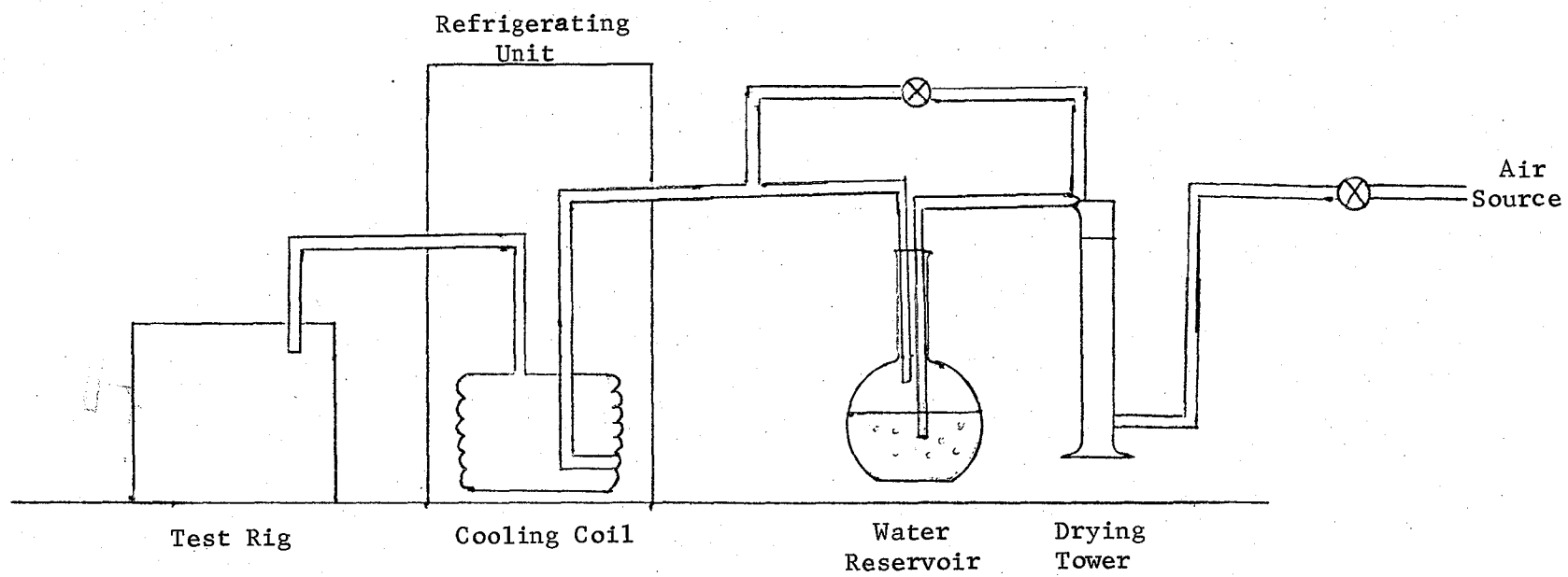


Figure I-12 Schematic of Humidity Control System

- (c) Introduce humidity controlled air into the system.
- (d) When the desired temperature and humidity are reached, allow test conditions to stabilize for one hour.
- (e) Apply load.
- (f) Turn on test motor and vary the velocity while monitoring friction force.

The results of the test run on smooth steel are plotted in Figure I-13. Three loads are shown, plotted with the coefficient of friction as a function of velocity (mph). There appears to be a very little difference between 40#, 50# and 60# loads. The major difference is in the level of friction for each humidity. At very low speeds the friction coefficient values varied between .13 to .45 depending on the relative humidity. At 50% humidity the values obtained were between .13 to .16. At 30% relative humidity the values obtained were between .27 to .32 and at 10% relative humidity the values obtained were between .39 to .45. As the speed increased, the values reduced to between .08 to .13. The lowest relative humidity always gave the highest friction coefficient. Essentially, the effect of humidity is much more pronounced at lower speeds than it is at higher speeds. Tests could not be run at higher relative humidity levels because of the frost buildup problem discussed previously. It is believed that the trend would continue at higher humidity level as long as the ice below the water does not soften.

It appears that the moisture added continuously to the ice surface is reducing the friction coefficient to the kinetic value (approximately .1). At the higher speed, the water is being produced at the surface due to frictional heating. Therefore the effect of adding water from the atmosphere is less.

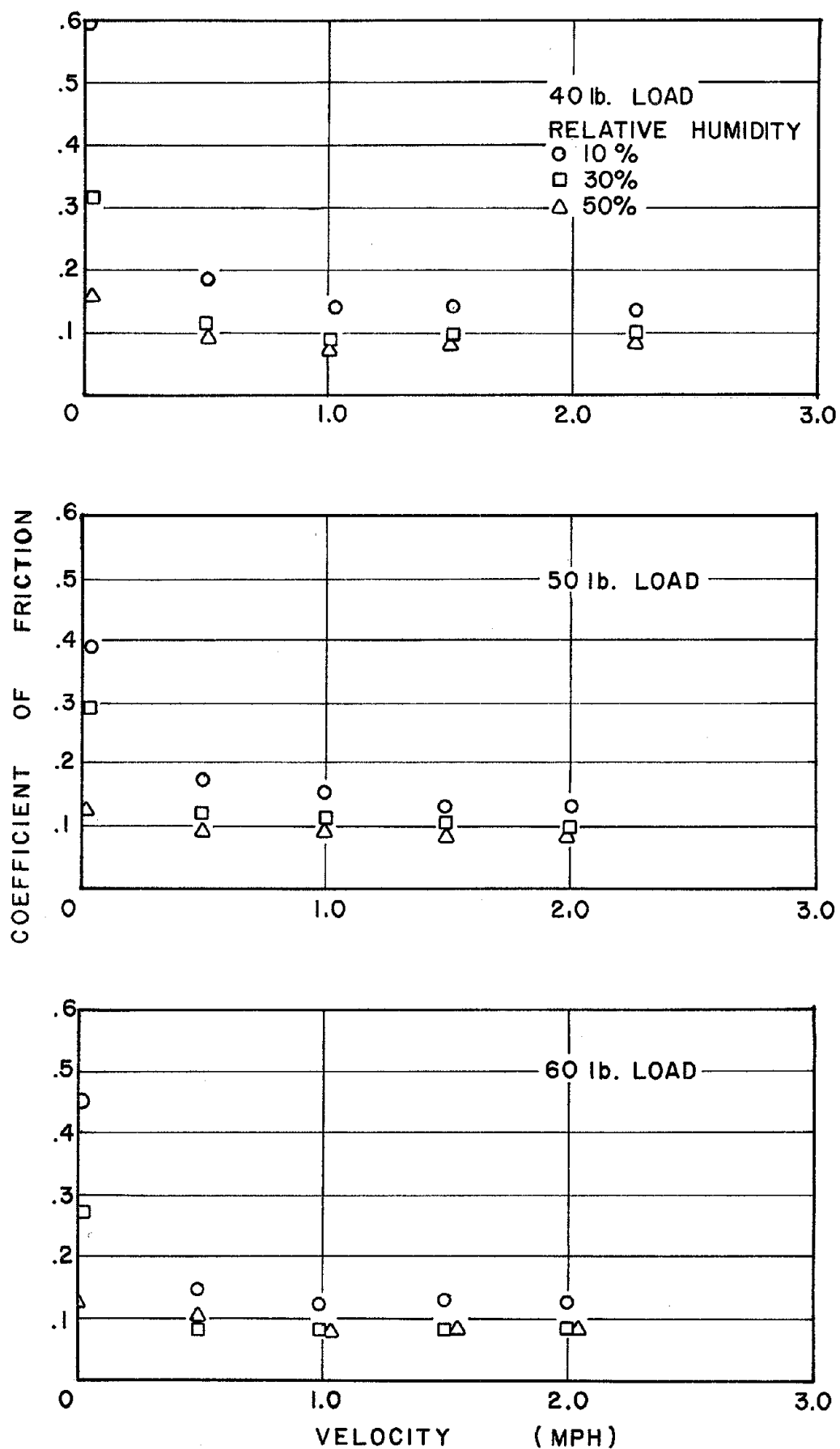


Figure I-13 Effect of Velocity on the Friction Coefficient of Steel Sliding Against Ice at Various Relative Humidity Environments

4.3 Effect of Humidity on Various Materials at Two Temperature Levels

The effect of humidity was measured on several materials other than steel.

The materials tested were:

- (a) Polyamide epoxy
- (b) Polyethylene
- (c) Polyurethane (nonsolvented)
- (d) Polyurethane chemical cure
- (e) Polyurethane moisture cure (elastomer).

The results of the test are seen in Figures I-14 and I-15.

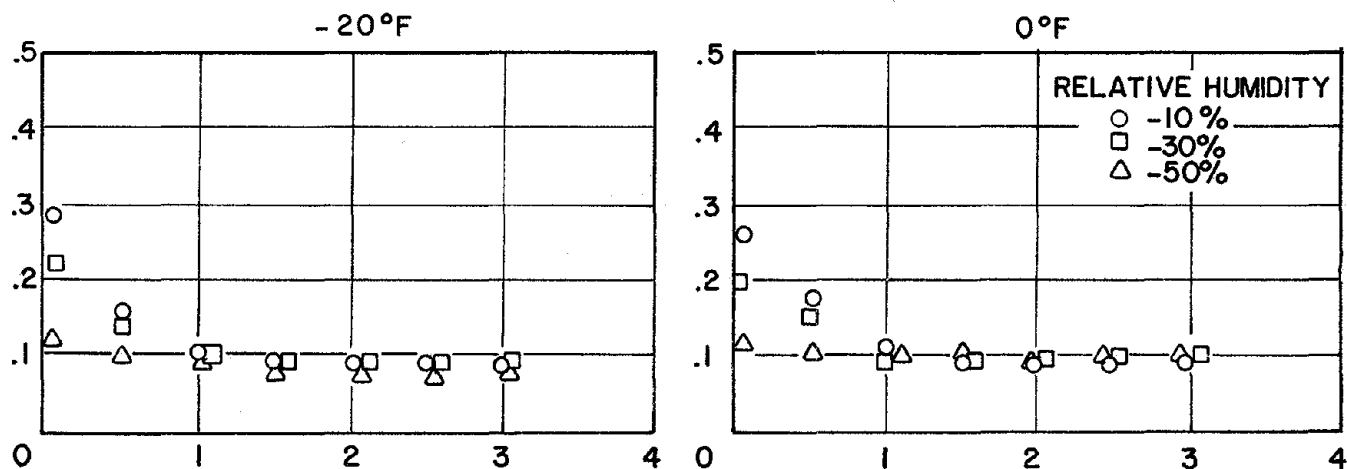
The trends noted are essentially the same as those seen in the steel tests (Figure I-13), i.e., lowest speed give the greatest difference. Lower humidity levels produced the highest friction coefficient at velocity levels below .5 mph.

4.4 Effect of Contact Area

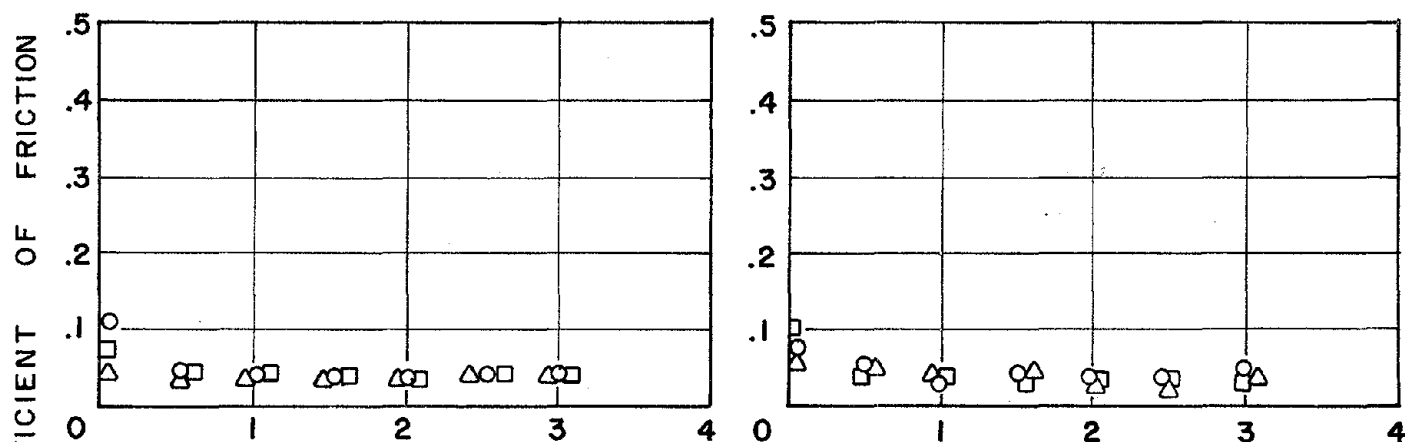
One of the most important friction factors to consider when studying the frictional behavior of a soft material is the effect of changing the area of contact. At light loads the friction is independent of contact area, however, at high loads the friction force can increase as the contact area increases. In order to study this effect friction tests were run with steel (130 CLA roughness) sliding against ice using three different contact areas: 2 in^2 , 1.5 in^2 and 1.3 in^2 . The effect of load on static and kinetic friction coefficient at a temperature of -20°C (-4°F) is shown in Figure I-16.

It can be seen that the friction coefficient is constant up to approximately 150 pounds load and thereafter begins to decrease. Furthermore, above 200 pounds the smallest area gives the lowest friction. In order to illustrate this effect all the data of Figure I-16 is replotted as friction coefficient

POLYAMIDE EPOXY



POLYETHYLENE



POLYURETHANE-NONSOLVENT

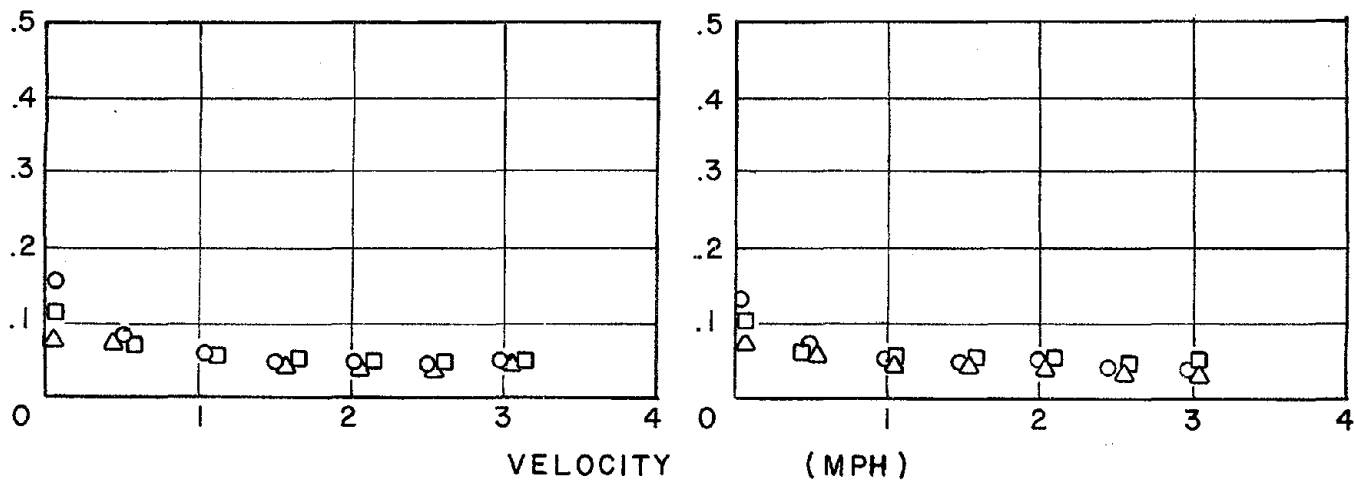


Figure I-14 Effect of Velocity on the Friction Coefficient of Various Materials Sliding Against Ice at Three Relative Humidity Levels

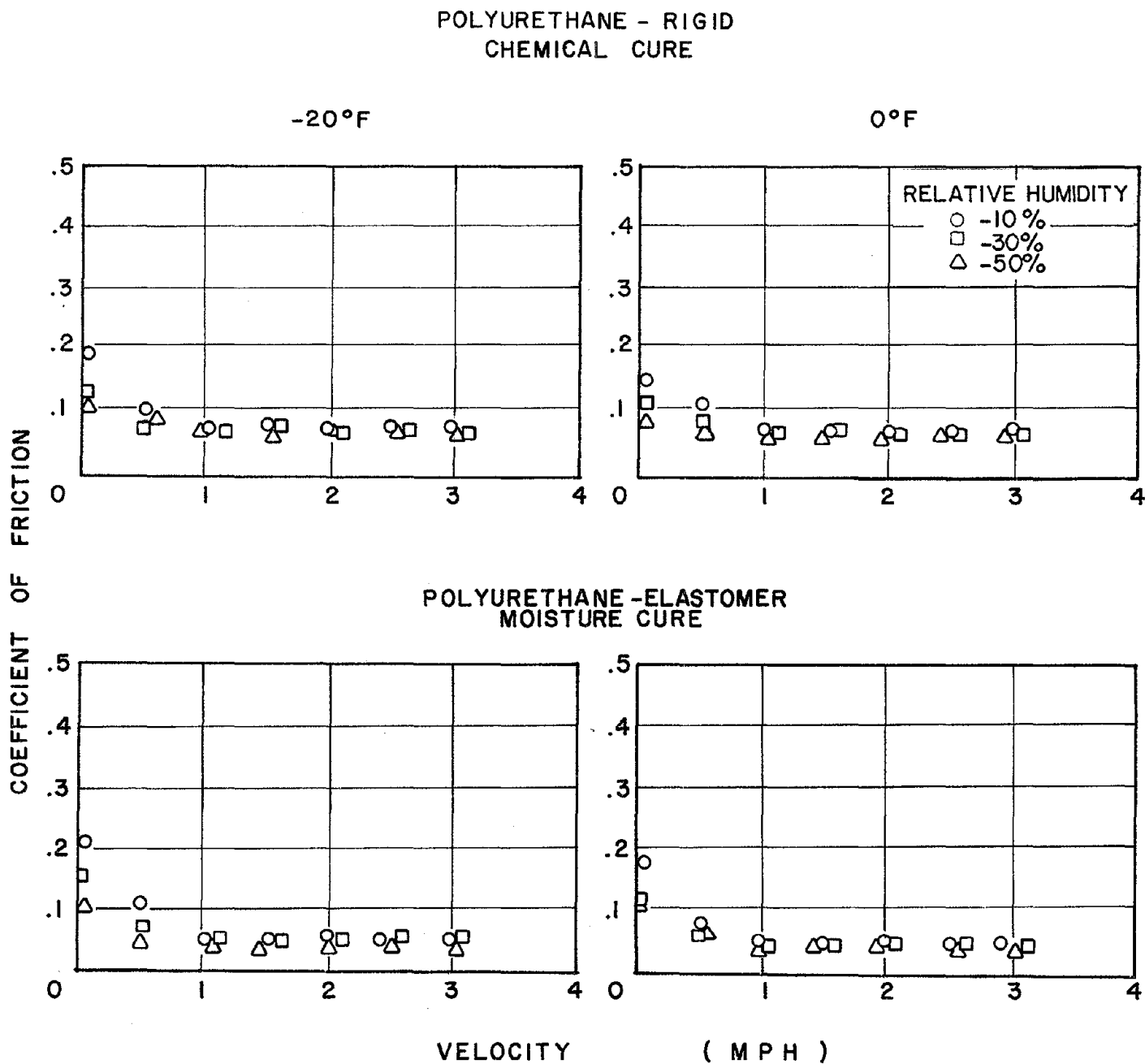


Figure I-15 Effect of Velocity on the Friction Coefficient of Various Materials Sliding Against Ice at Three Relative Humidity Levels

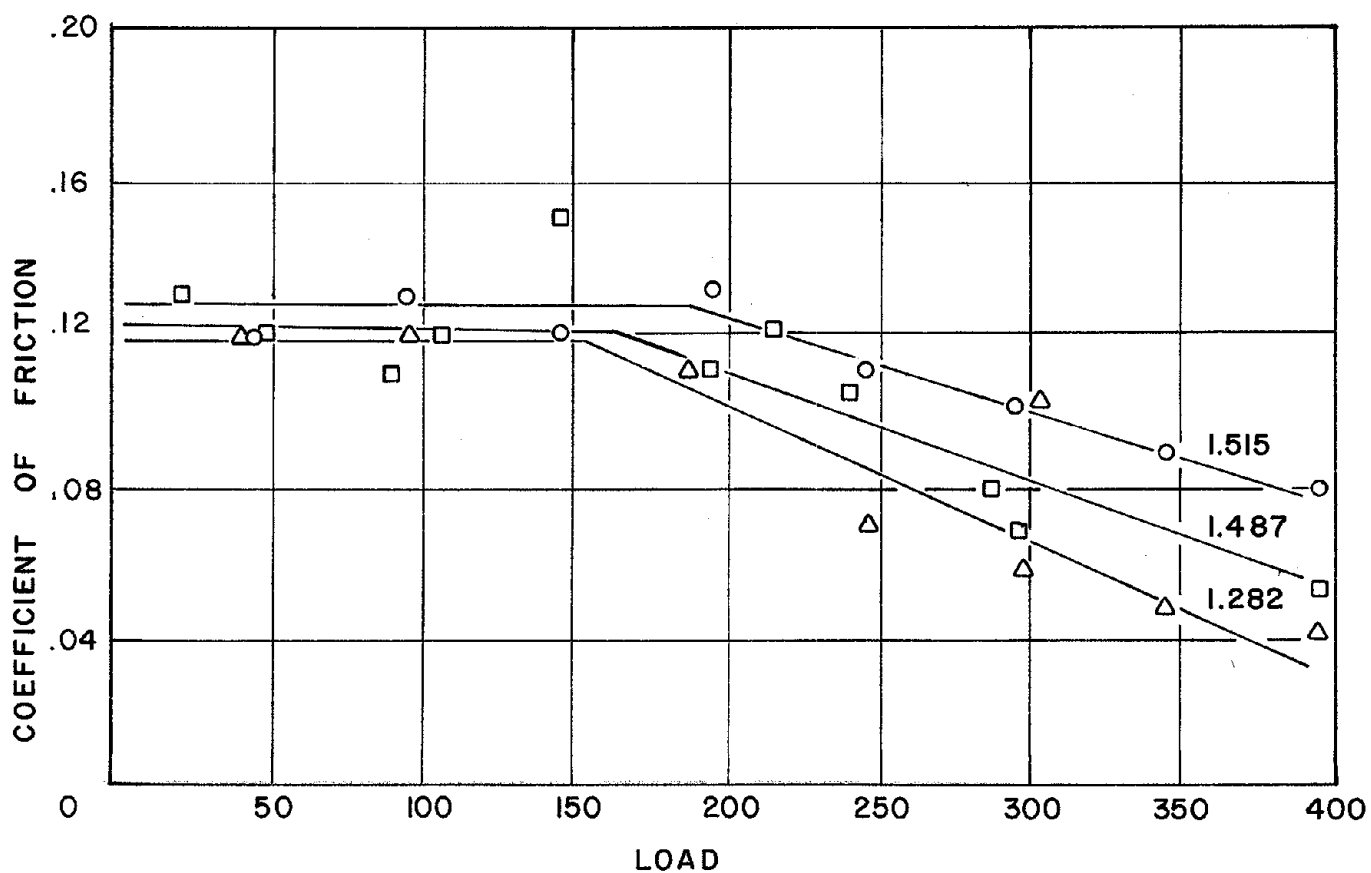


Figure I-16 The Effect of Load on the Coefficient of Static and Kinetic Friction for Steel Sliding Against Ice Using Three Different Areas of Contact. Roughness 130 CLA, Temp. -20°C (-4°F)

vs reciprocal pressure in Figure I-17. When plotted in this manner it is seen that all of the data for each type of friction plots as a single straight line. At these high loads the static friction is somewhat erratic but the extension of the kinetic friction line is seen to pass through the origin. This is an effect which has previously been investigated by the authors (Ref.6). It is explained in its simplified form as follows:

The friction coefficient for any material combination is

$$f = \frac{A_r S}{L} \quad \begin{array}{l} A_r = \text{real area of contact} \\ L = \text{Load} \\ S = \text{Shear strength of the ice} \end{array} \quad (1)$$

At low pressures the surfaces in contact touch at only a few points so $A_r \ll A_a$ where A_a is the full area as defined by the specimen geometry. As the load is increased it has been found that A_r increases directly with the load so that as long as S remains constant, f remains constant with increasing load. This proportionality holds (it was found) till the pressure reaches the yield strength of the material. At this point the real area A_r approaches A_a and can increase no further. At this point

$$A_r \approx A_a = \text{constant.}$$

Thus if the load is increased above the point

$$p = \frac{A_r}{L} = y \quad \begin{array}{l} y = \text{yield strength} \\ p = \text{pressure} \end{array} \quad (2)$$

then f must decrease since both $A_r = A_a$ and S are constant.

The manner in which f decreases is illustrated by Figure I-17. Substituting from Eq.(2) the pressure p , Eq.(1) becomes

$$f = \frac{S}{p} = S \left(\frac{1}{p} \right) \quad (3)$$

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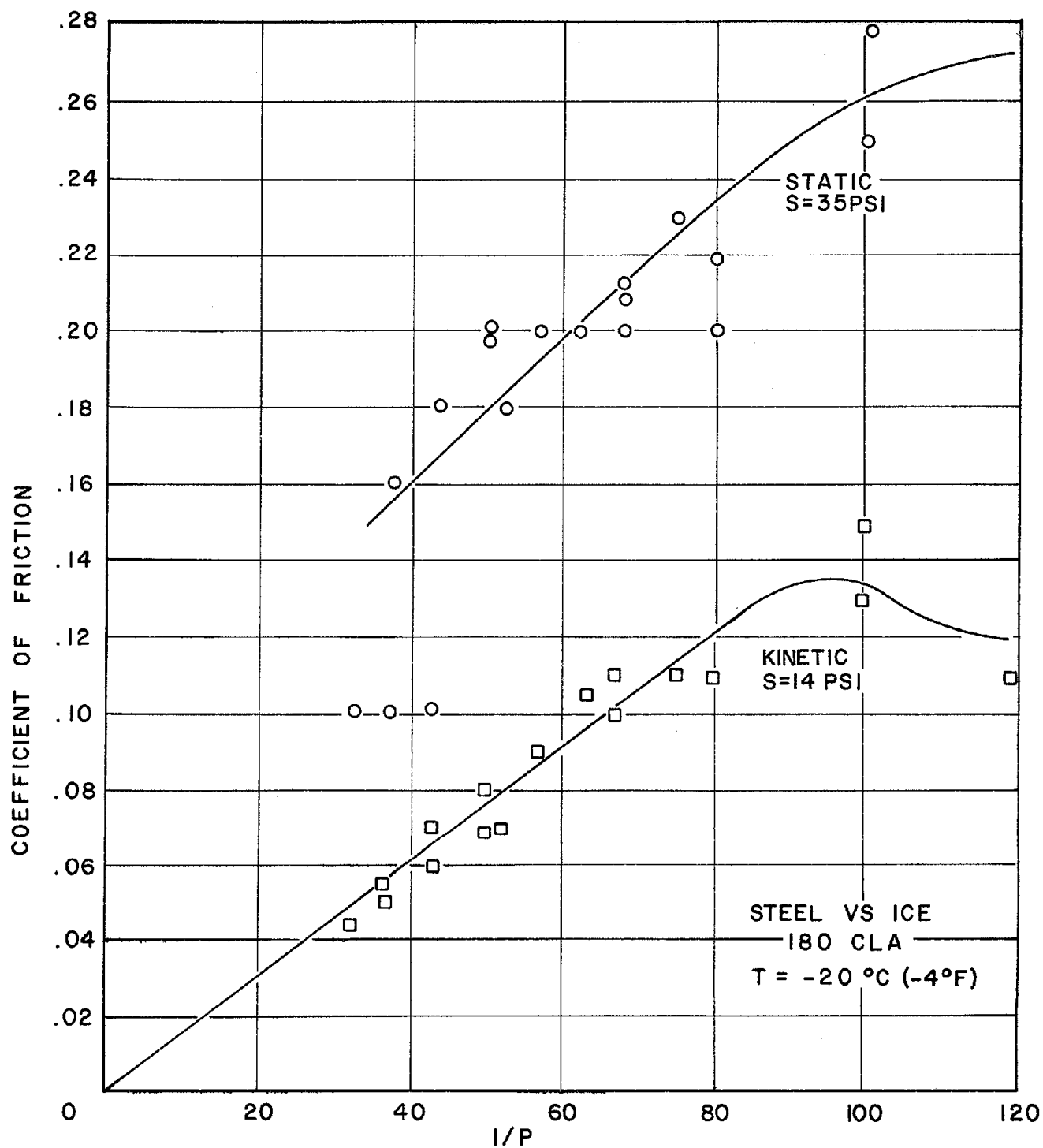


Figure I-17 Effect of Pressure on the Coefficient of Friction

Thus if f is plotted against $\left(\frac{1}{p}\right)$ a straight line will result of slope S if S is constant. In Figure I-17 it can be seen that this is the case for both static and kinetic friction, where $S_s = 35$ psi and $S_k = 14$ psi.

Thus as seen from Figure I-16 and from Figure I-17 there are two basic regimes of friction as the pressure is increased:

Regime I	$p < y$	constant friction	$f = \text{constant}$
Regime II	$p > y$	constant surface shear stress	$s = \text{constant}$

This is illustrated in Figure I-18 where friction coefficients are plotted against pressure. Note that friction is constant up to $p \approx 100$ psi and then begins to decrease. Thus this denotes the transition point between the two regimes. The use of Figure I-18 in calculating hull friction resistance is described in a later section.

These data were obtained at single values of roughness and temperature. Although the frictional behavior changes in a predictable way with both temperature (Fig.I-4) and roughness (Fig.I-3) further data, similar to Figure I-18, should be obtained at different roughnesses and temperatures to insure the generality of the concept.

When related to the geometry of an icebreaking hull it is postulated that the friction regime II would exist from the bow to the maximum beam of the hull. As the width decreases from the maximum beam dimension (approximately midship to stern), friction regime I would exist when no icebreaking or crushing is occurring as a result of submerged ice jamming between the hull and the ice field. If crushing occurs probably regime I and II would exist and the dominant forces would depend on the amount of crushing taking place.

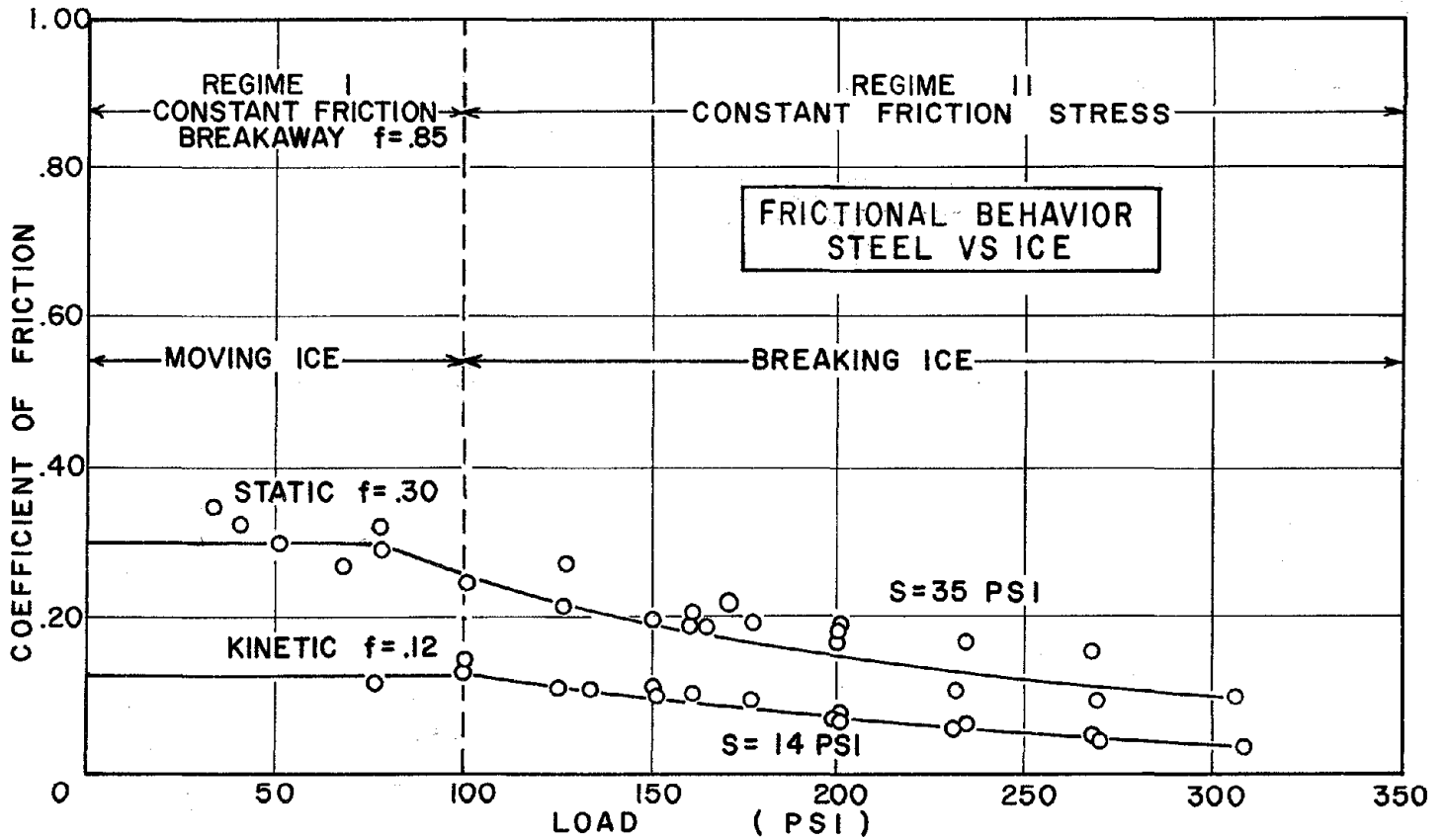


Figure I-18 Effect of Load on the Coefficient of Friction for Three Different Contact Areas. Roughness 130 CLA, Temp. -20°C (-4°F)

4.4.1 Sled Tests to Determine the Area Effect

The effect of area in contact on the frictional properties of ice is a variable which is extremely important in determining icebreaking friction. These data, however, were obtained with small laboratory test specimens and some more practical, field data were desired. Accordingly, some sled tests were run.

A steel sled was manufactured which would accept heavy loads. One surface of the sled had two runners 3" \times 26". The opposite surface was a flat surface 28" \times 44". All edges were chamfered to reduce the possibility of edge loading. The load could be applied to either surface with the ice contact on the opposing side.

The weight was applied with a 55 gallon drum of lead weighing 5,200 lbs. The weight of the sled alone was 210 lbs.

The sliding surfaces were grit blasted to a surface roughness varying between 310 and 400 μ " CLA (.1 cut-off).

The friction force was measured through a Strain-Sert Bolt (SYS-FB) connected in series on a chained yoke between the sled and a fork lift. The connection at the bolt was made flexible to eliminate residual forces due to misalignment. The friction forces were measured on a BAM1 Vishay Instruments Inc. Bridge Amplifier and Meter and recorded on an Analog Recorder. Photographs of the loaded sled, and the Strain-Sert Bolt arrangement are seen in Figure I-19.

The testing was performed on an indoor ice rink. Therefore the test conditions could be controlled and recorded. Air temperature, ice temperature and relative humidity were measured.

The test conditions were as follows:

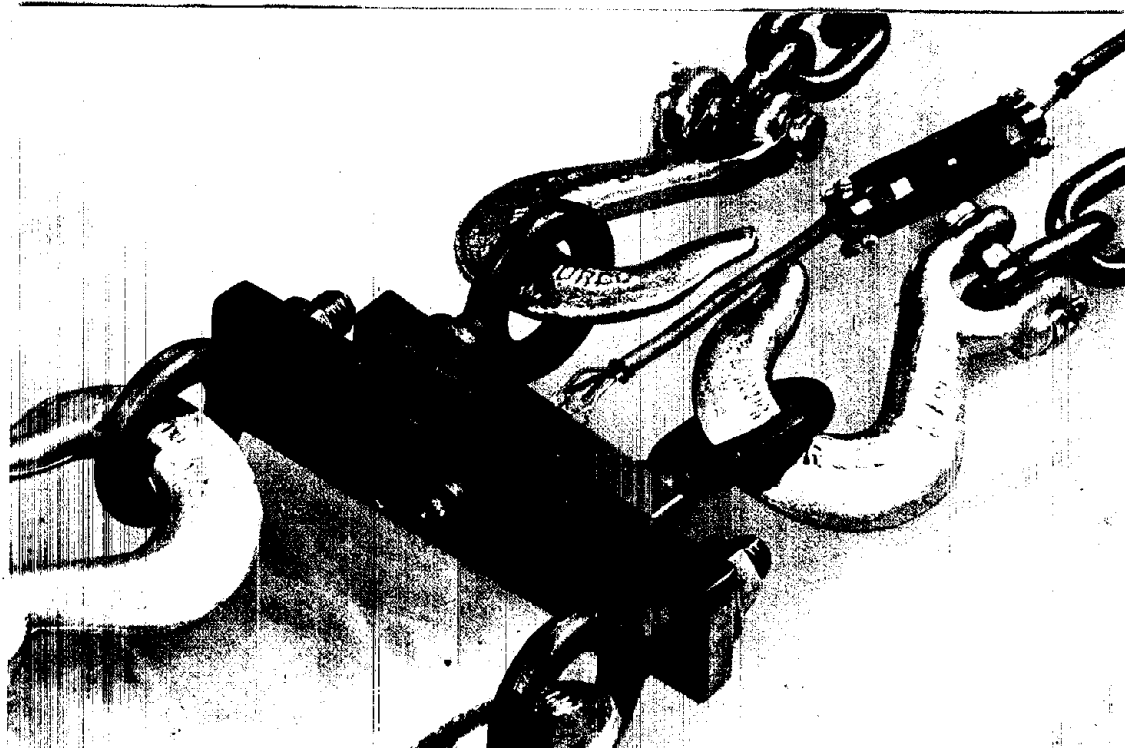
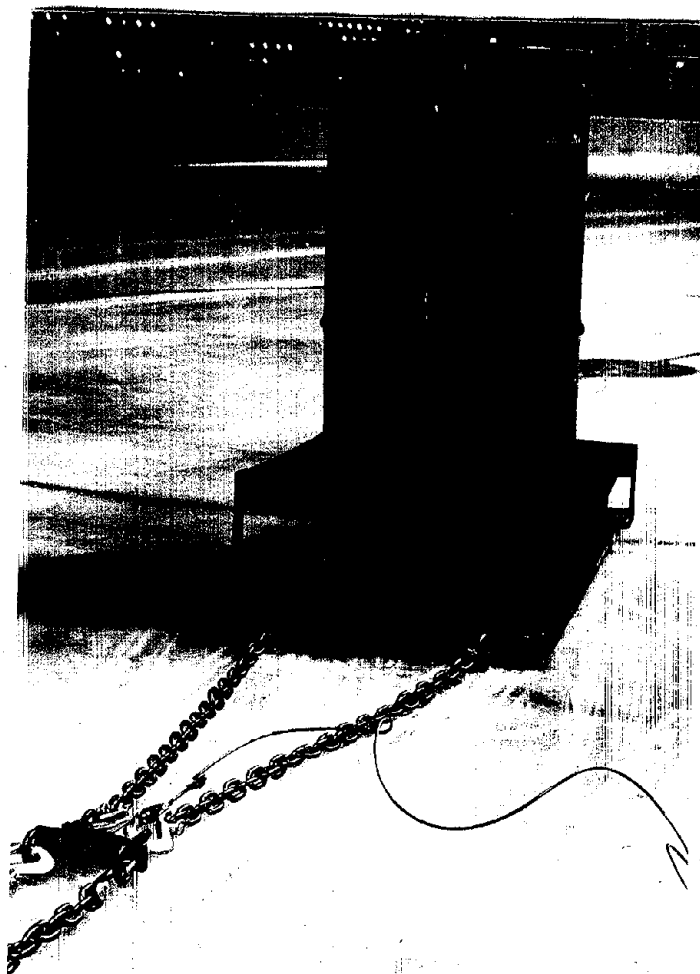
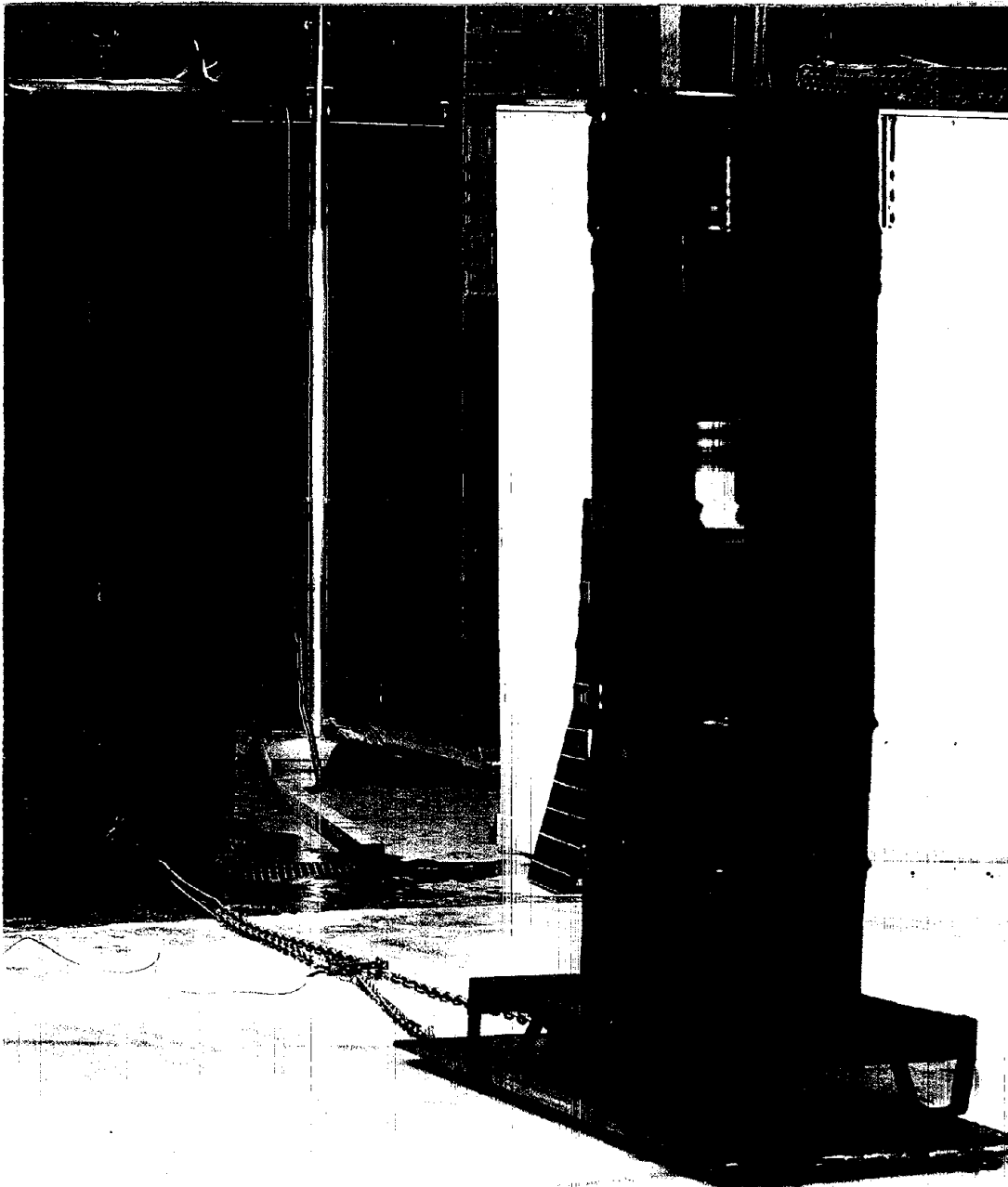


Figure I-19 Strain Sert Bolt Arrangement Used to Measure the Friction of Steel Sliding Against Ice Under High Loads



air temperature	7°C (45°F)
ice temperature	-9°C (17°F)
relative humidity	17%
surface roughness of the sled (flat and runner surfaces)	310 to 400 μ " CLA
speed	0 to 5 mph (estimated).

The results of the test are seen in Table I-1. The friction coefficient of the sled alone on runners running against dry ice was .2 breakaway and .13 to .1 dynamic.

The friction coefficient of the runners on dry ice with 5400 pound load was approximately .44 breakaway and .22 to .1 dynamic.

After applying water to the surface of the ice, the runner friction had increased during breakaway and decreased during the dynamic. The decrease in friction is not significant. On ice the average friction coefficient is .23 decreasing to .096 and on the wet ice the average is .20 and decreases to .095.

A comparison of dry ice values for the runner and flat surface show a significant increase both in breakaway and dynamic friction. The large area produces a friction coefficient which oscillates between .72 and .10. The test rig exhibits severe stick slip during the run and essentially changed in direction while being pulled. It is not known if this is a directional instability effect or if it is caused by stick slip action usually seen at the interface of sliding surfaces. The overall result was a significant increase in friction force.

After adding water to the ice surface the breakaway friction increased drastically. This was attributed to the water freezing to the sled and the ice. After breakaway however, the sled moved very easily on the wet surface producing very low values of friction.

TABLE I-1

Readings	Sliding Surface	Load	Pressure (psi)	Area	Ice Condition	Breakaway	Slow	Medium Speed	High Speed - 5 mph*	Remarks
1	Runner	210#	1	216 in ²	Dry	.2	.13	.1	.1	
2	Runner	210#	1		Dry	.2	.13	.1	.1	
1	Runner	5400#	25	216 in ²	Dry	.44	.22	.14	.09	
2	Runner	5400#	25		Dry	.62	.22	.16	.1	
3	Runner	5400#	25		Dry	.46	.26	.14	.1	
1	Runner	5400#	25	216 in ²	Wet	1.1	.20	.1	.1	
2	Runner	5400#	25		Wet	.54	.20	.14	.09	
1	Flat	5400#	4.3	1232 in ²	Dry	.72	.72-.12	.6-.12	.6-.12	Severe stick slip after breakaway
2	Flat	5400#	4.3		Dry	.40	.68-.1	.65-.1	.6-.1	
1	Flat	5400#	4.3	1232 in ²	Wet	.52	.05	.05	.05	Immediately after breakaway, test sled moved across the surface very quickly
2	Flat	5400#	4.3		Wet	1.3	.05	.05	.05	
3	Flat	5400#	4.3		Wet	1.3	.05	.05	.05	

* Estimated speed

Friction Measurements Obtained on a Test Sled Sliding Against Ice

It should be stressed that these values are seen on hard ice and on water on hard ice. The ice condition and temperature appear to have a very strong effect on the frictional properties. The closer the temperature is to freezing, yielding is likely and the water effect should be negligible. However, the hard ice is able to support the load.

4.4.2 Conclusion

As was found in the bench tests the large area gave much higher friction force values than the smaller area at a given load. Sliding takes place by a "stick slip" action which is not seen on the smaller areas (runners) even though the load was the same.

The addition of water to the ice surface gave little change in friction, unless it causes the freezing together of the two surfaces. If this happens a significant increase in the breakaway friction occurs.

4.5 Sled Tests on Model Ice

Tests were run in ice which were prepared at the Arctec Model Test Basin to determine the frictional values obtained on model ice sliding against various test surfaces. The air temperature, ice temperature and relative humidity of the room were measured and recorded. A test fixture was made which would accept 1" sq test specimens coated with various coatings or surface preparations. Figure I-21 shows the test fixture used. The essential parts are, the test specimen, housing, strain gage transducer, loading mechanism and dead weight loads.

The test specimen is placed in contact with the ice and pulled through the strain gaged transducer. The friction force was recorded on a Bridge Amplifier and an analog recorder.

The flexure strength of the ice was .4 gram/sq cm (.0056 psi). The thickness of the ice was approximately 1". The model ice is produced with reduced strength to simulate the ice encountered during icebreaking. It is grown in needle-like crystals with the needles oriented perpendicular to the water surface. The strength of the ice is extremely weak; a 3 in. long piece held at one end will not support its own weight.

The ice was removed from the test basin with a piece of plywood floated under the surface and then lifted with the ice on top. A piece of ice approximately 12" wide by 18" long was the maximum size that could be removed without cracking. Even using the plywood technique, if any small piece of ice floated between the wood and the ice, the ice would deform over the particle and crack.

During the test, all test fixtures and surfaces had to be placed in contact with a second piece of ice in order to keep the temperature of the steel surface close to the temperature of the ice. Otherwise the test specimen and fixture would immediately melt into the ice surface.

The tests were run under the following conditions:

Air temperature - 4.4°C (40°F)

Humidity - 70 to 90%

Load - as indicated

Velocity - approximately .5 ft/sec

Ice temperature - -1.1°C (30°F)

Ice condition - saline water - salinity adjusted to obtain flexure strength needed.

During the test, edge loading was noted on the ice surface after sliding. As this occurred, the force trace would immediately peak. These peaks were not incorporated into the friction calculation but are noted in the tables which show the test results. Since the strength of the ice was low, very light

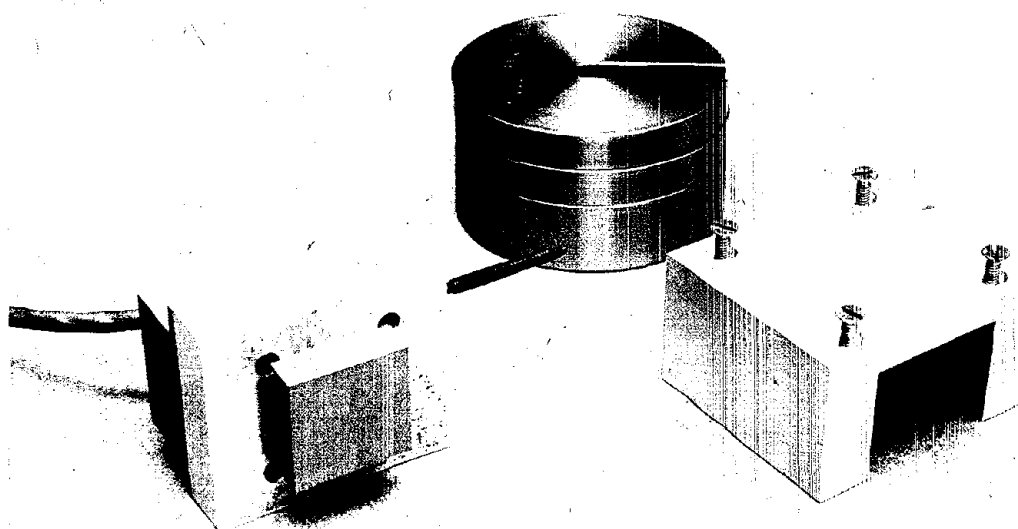
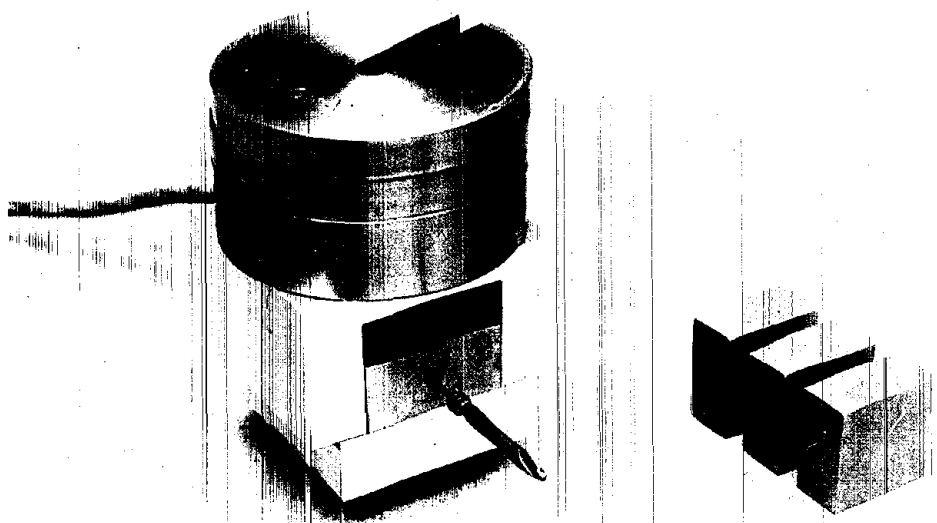


Figure I-21 Test Apparatuses Used to Measure the Friction of Various Surfaces Sliding Against Model Ice

test specimen loading was applied to the test fixture, otherwise ice deformation would occur forcing the test fixture to cock.

The test results are seen in Table I-2. The dynamic friction values show that the friction for all of the materials is very similar to those seen in the original laboratory evaluation at the same temperature (approximately 30°F) and roughness (130 CLA) (Figure I-5). The increased surface roughness (160 μ "") gave significantly higher friction over the smooth surface (11 μ ""). Since the temperature of the ice is very close to melting, asperities in the steel surface dig into the weak ice. The ice cannot support high loads and therefore movement between the two surfaces (steel - ice) results in flowing. The smoother surface (11 μ "") produces lower friction levels since less asperities exist on the surface and therefore less surface deformation (plowing). The results also indicate a significant reduction in friction for surfaces coated with polyurethane when compared to steel with similar surface roughnesses. They also show that a significant drop in friction occurs between the steel and coated surfaces and as the surface roughness decreases.

A second series of tests were run on a sled arrangement as shown in Figure I-22. The sled was 1/10 scale model of the sled used in earlier tests on hard ice. The essential parts are (a) the sled with two runners on one sliding surface and a flat surface opposite it. The sliding surface could be either side, depending on the surface area desired; (b) an aluminum holder for applying the loads; (c) a load cell transducer used to pull the sled and measure the friction force; (d) dead weight loads. The test conditions and type of ice are the same as those described in the previous section on model ice.

The test results are shown in Table I-3. Essentially the friction coefficient of .8 was given for both the sled runners and the flat. There appeared to be no difference in the friction coefficient with a given load. These

TABLE I-2

RESULTS OF THE TESTS OF VARIOUS MATERIALS SLIDING AGAINST MODEL ICE

Material	Surface Roughness (CLA)	Load lbs	f	Remarks
Steel	11 μ "	1.1	.3	Peaked at .6
Steel	11 μ "	.85	.35	Peaked at .6
Steel	160 μ "	1.1	.8	Peaked at 1.1
Steel	160 μ "	.85	.75	Peaked at 1.2
Epoxy*	13 μ "	1.1	.25	Peaked at .45
Epoxy*	13 μ "	.85	.28	Peaked at .52
Epoxy*	85 μ "	1.1	.60	Peaked at .73
Epoxy*	85 μ "	.85	.64	Peaked at .80
Polyurethane ⁺	10 μ "	1.1	.12	Peaked at .52
Polyurethane ⁺	10 μ "	.85	.10	Peaked at .40
Polyurethane ⁺	25 μ "	1.1	.18	Peaked at .25
Polyurethane ⁺	25 μ "	.85	.20	Peaked at .30
Polyurethane ⁺	135 μ "	1.1	.43	Peaked at .60
Polyurethane ⁺	135 μ "	.85	.45	Peaked at .60

* Polyamide

⁺ Rigid urethane (chemical cure)

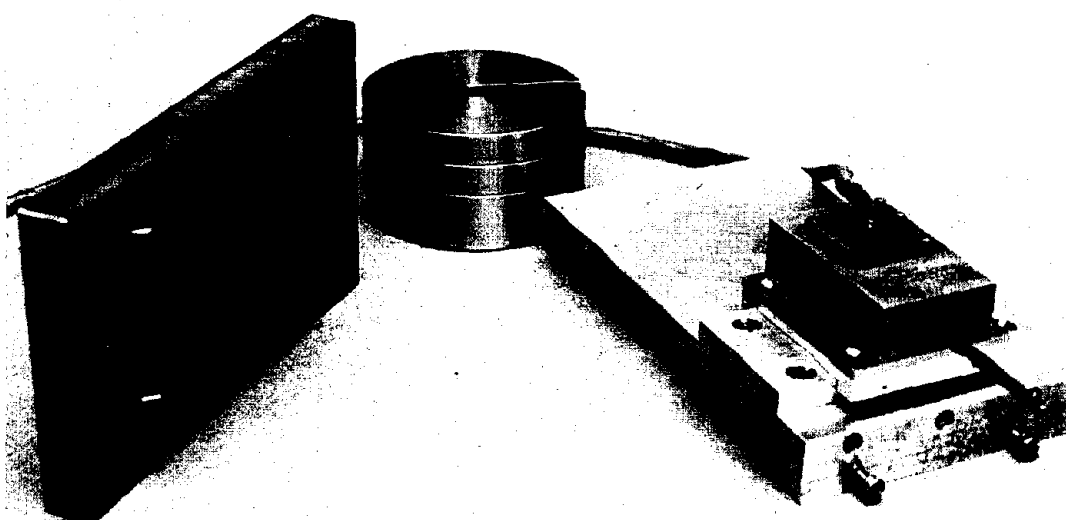
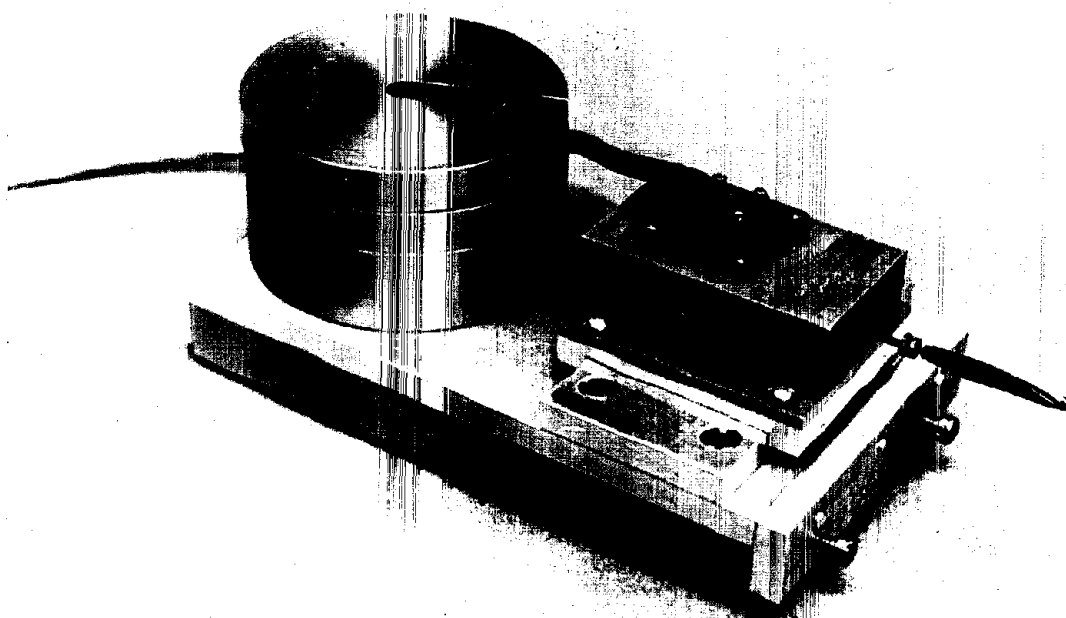


Figure I-22 1/10th Scale Model of the Test Sled Used to Evaluate Area Effects on Model Ice

TABLE I-3

TEST RESULTS OBTAINED ON THE 1/10 MODEL SLED SLIDING AGAINST MODEL ICE

Load	Area	Surface Roughness (CLA)	f	Remarks
3 lbs	Flat	160 - 180 μ "	.8 to 1.1	Peak values obtained from edge loading
3 lbs	Flat	160 - 180 μ "	.75 to 1.1	" " "
3 lbs	Flat	160 - 180 μ "	.78 to 1.2	" " "
3 lbs	Runners	195 - 240 μ "	.79 to 1.1	" " "
3 lbs	Runners	195 - 240 μ "	.83 to 1.1	" " "
3 lbs	Runners	195 - 240 μ "	.76 to 1.2	" " "

friction levels are consistent with the tests run on similar ice (Fig.I-4) at similar surface roughness.

4.5.1 Conclusion

The results show an inconsistency with the sled tests run on hard ice (Table I-1) but is predictable since the ice strength and hardness is different. During the large scale tests the ice was hard because of the low temperature (-9°C , 17°F) while with the 1/10 scale model test, the ice was extremely soft because the temperature (-1.1°C , 30°F) was very close to melting. Therefore the increased friction as predicted in Figure I-4 at temperatures near the melting point of ice will produce high friction values.

Similar model tests should be run using the 1/10 scale sled on hard ice to study the area effect seen on the full size sled. Model ice is made for the specific purpose of scaling the ice flexural strength. The friction coefficient is usually varied during model testing by varying the surface roughness of the model hull. The coefficient of friction is not established during model testing but decided upon before the test and the friction is measured by sliding ice on the hull surface and varying the roughness until the desired coefficient of friction is obtained.

It should be noted however that the conditions under which the friction measurements are taken must match the conditions of the ice in the model test basin. The velocity, temperature and humidity must be carefully monitored and controlled during the friction tests to simulate the conditions during model testing.

4.6 Effect of Coating Thickness on the Frictional Coefficient of an Epoxy Sliding Against Ice

A series of tests were run to determine the effect of coating thickness on the frictional behavior of ice.

The material tested was an epoxy polyamide coated at three different thickness levels. They were 2 dry mils, 20 dry mils and 60 dry mils.

The tests were run under the following conditions:

Temperature	-17°C (0°F)
Relative Humidity	5%
Velocity	0 to 2 mph
Load	70#
Surface Roughness	20 μ " CLA.

The results of the tests are plotted in Figure I-23. The data indicates no significant change in friction coefficient of this material sliding against ice as a function of coating thickness. The difference in data obtained on the three coating thicknesses are a variation of friction coefficient of .26 to .31 at the low speed and .085 to .1 at the highest speed.

The purpose of this test was to determine the effect of coating thickness. The results of the friction test indicate that for thickness between .002" and .060" there did not appear to be a change in the friction. This is believed to be significant for all coating materials as long as the hardness of the coating is high enough to resist deformation at low temperatures.

4.7 Frictional Behavior of Ice

In order to propose a working model for ice friction it is first necessary to outline the various effects which must be explained. These effects are as follows:

- (1) Friction varies with the strength of the ice as indicated by changes with temperature (Fig.I-4).
- (2) Static friction increases from 0.27 to 0.80 with roughness, kinetic friction (page 51, Ref.2) increases only slightly from .08 to .11.

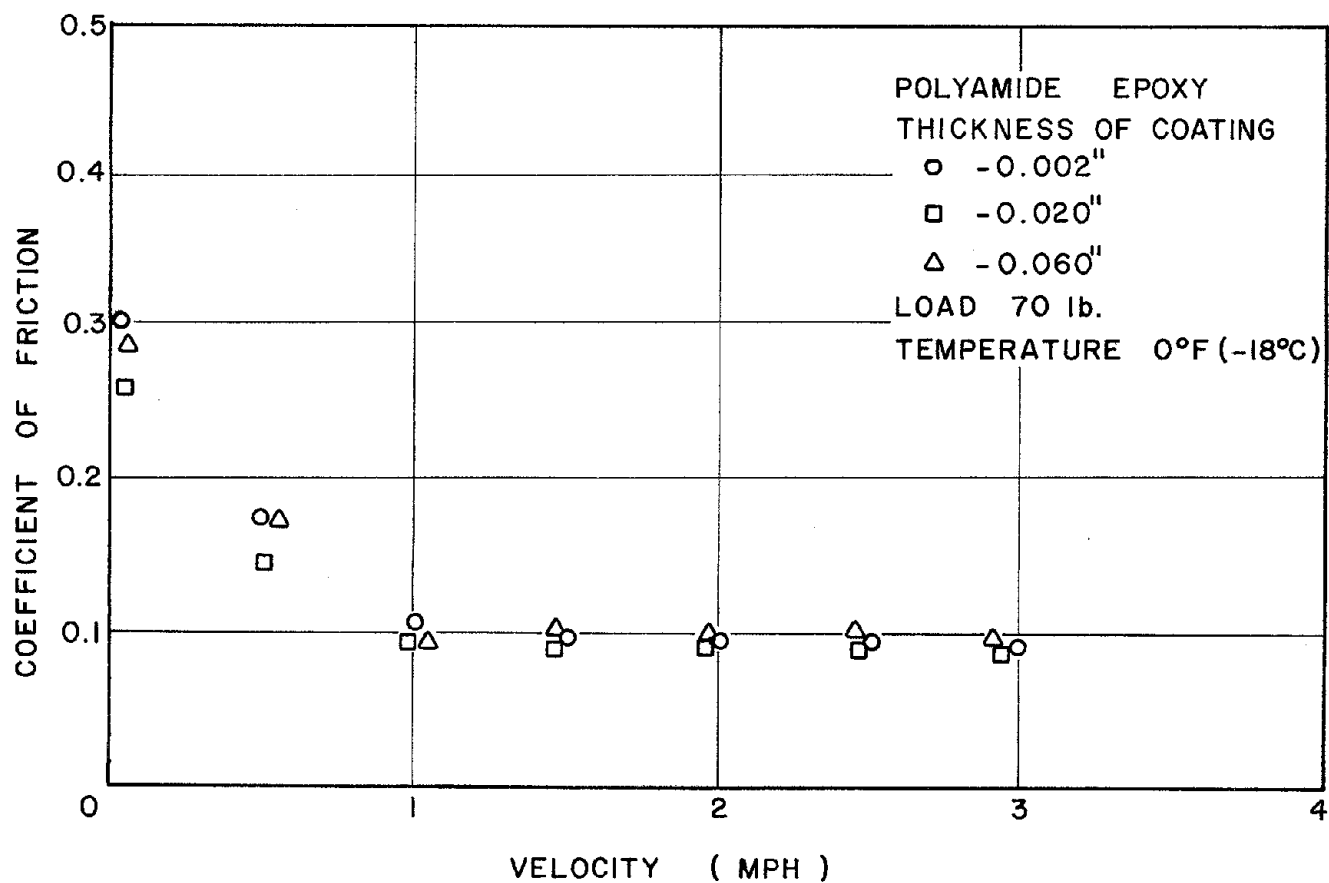


Figure I-23 Effect of Coating Thickness on the Frictional Properties of Ice

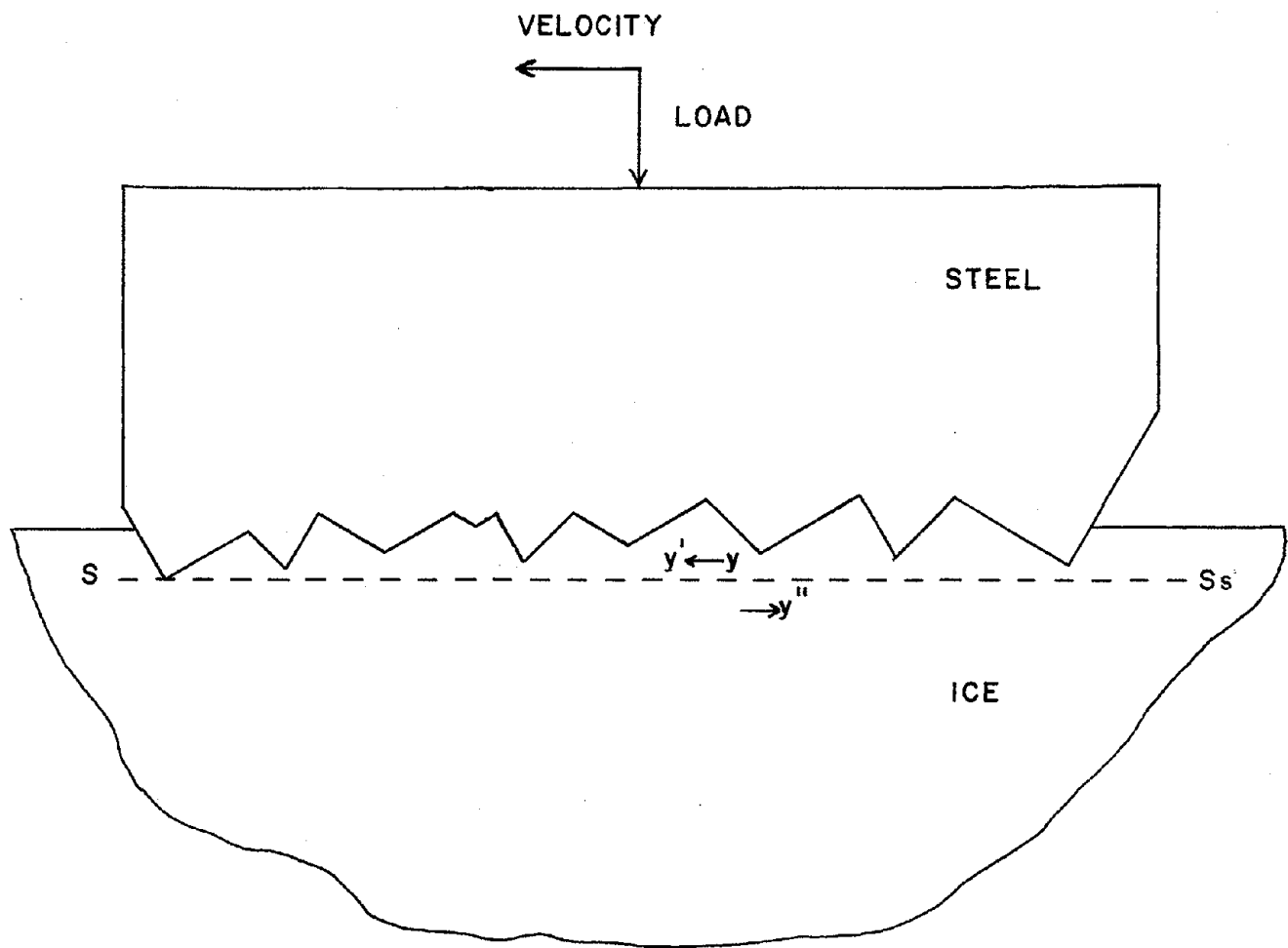
- (3) Friction decreases with low adhesion materials (Fig.I-3).
- (4) Friction increases with time in contact and decreases with velocity (page 48, Ref.2 and Fig.I-7).
- (5) Static friction decreases with humidity, kinetic friction does not (Fig.I-13).
- (6) With rough surfaces, friction increases significantly as the melting point is approached (Fig.I-4).

To explain this behavior the model proposed in Ref.6 can be extended; this was extensively investigated for soft metals.

A diagram of a rough steel surface loaded against ice is shown in Figure I-24. The load is greater than 100 psi so that the full contact area is involved. In order for slip to take place at the surface the ice must somehow be deformed, the steel is considered to be rigid. Deformation is only possible in two different ways; shear or fracture along the line SS_s (Fig.I-24A) or deformation in the direction SS_p (Fig.I-24B). If deformation takes place along SS_p it must be accompanied by interface slip along the line SS_i .

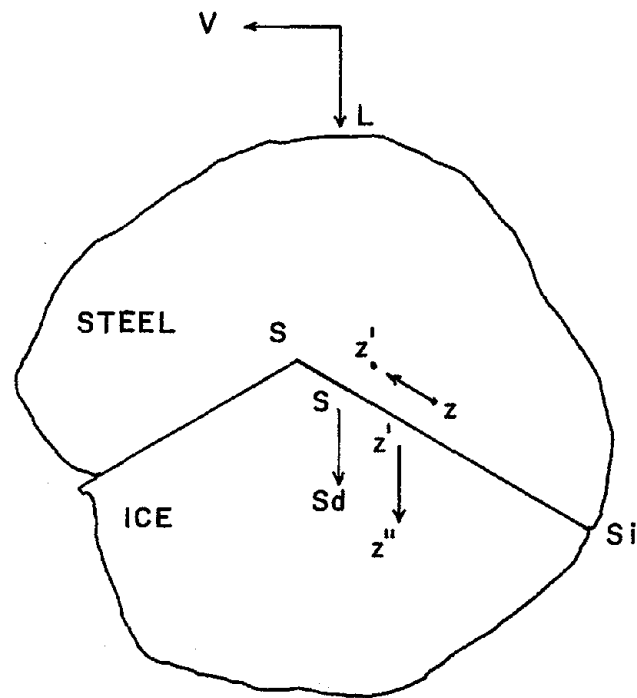
If shear takes place along the line SS_s (Fig.I-24A) two points in contact at point y will be at y' and y'' after shear.

If deformation takes place along the line SS_p (Fig.I-24B) then two points originally at z will be at z' and z'' after deformation. It is clear that the points z' and z'' are displaced along SS_i so interface slip must have taken place. This deformation process may be more clearly visualized by considering what must happen if the ice is moving to the right in Figure I-24B. In order to flow around the point " S_i " the ice must both be deformed downward and slip at the $S - S_i$ interface. It must do this around each asperity within the contact area.

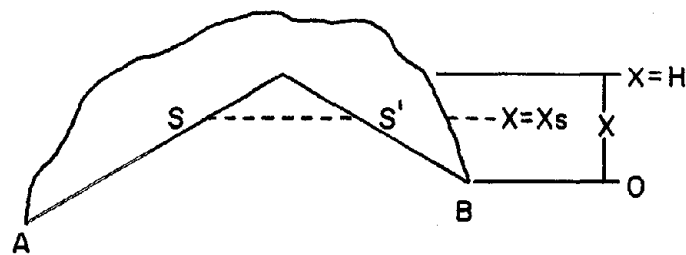


(A) MULTIPLE ASPERITY (SURFACE SHEAR)

Figure I-24A Model of the Frictional Behavior of Ice



(B) SINGLE ASPERITY (ASPERITY DEFORMATION)



(C) SINGLE ASPERITY

Figure I-24B and C Model of the Frictional Behavior of Ice

A combination of these two modes is also possible (Fig.I-24C). In this case shear would take place along the line SS' . In this case friction would be a combination of shear S_s , deformation S_p and interface slip S_i . That is, the sliding process consists of shear across the line SS' , deformation of the volume $ASS'B$ downward sufficiently to allow the passing of the asperity B; and slip across the interface $S'B$ to accompany the deformation of $ASS'B$.

From geometrical considerations it seems likely that this later model would apply. At $x = 0$, S_p (shear stress) is a maximum and decreases rapidly as $x \rightarrow h$. However, the sum of S_p and S_i is 0 at $x = 0$ and would be a maximum at $x = h$. Thus at some intermediate point $x = x_s$ the minimum shear force would be anticipated.

If this hypothesis is true, the friction of ice is a function of both the shear strength of ice and the interface slip since slip is taking place along the line $ASS'B$. As the temperature of the ice increases its strength decreases and static friction decreases. Static friction decreases with low adhesion materials since the interface S_i is lower.

Higher roughness gives higher static friction because the asperities have been shown to be more pointed (Ref.7) and more deformation takes place at a given load. With kinetic friction there is less effect of roughness because the interasperity regions fill with ice and slip takes place along the line SS_s . This is possible under kinetic friction conditions since the frictional heat has formed the lubricating layer along that line. The fact that such a layer forms is indicated by the friction-temperature data.

Note (Fig.I-4) that as temperature is increased the static friction and kinetic friction approach each other at temperatures above -5°C ($+22^{\circ}\text{F}$). Thus it can be proposed that the frictional heat forms a thin lubricating film of water. Thus the kinetic friction is independent of the ambient temperature

since the layer of water determines the frictional behavior not the strength of the ice (which varies with ambient temperature).

Humidity has basically the same effect as temperature and velocity. It supplies a thin lubricating molecular film of water which decreases adhesion. As is found for temperature and velocity it affects the static friction rather than the kinetic.

The large increase in friction as the temperature approaches 0°C (32°F) was noted. This can be explained by the fact that the ice collected in the metal asperities is removed by melting at the higher temperatures. Independent experiments with ice sliding against very rough steel surfaces confirmed this fact. At low temperatures the transfer of ice and the filling of the asperities was obvious. As the temperature was gradually increased the ice was observed to disappear and friction increased drastically.

The effect of time in contact is similar to that usually found in friction experiments. In longer time periods, improved adhesion bonds can be formed which increase friction.

Although the proposed frictional model is speculative, it is the only one which can be proposed which explains all the experimental observations. In order to prove that this model is the correct one, it must be formulated mathematically and used to predict the variation of friction with, for example, temperature, roughness and pressure. This was reserved for future work.

4.8 Frictional Resistance in Icebreaking

The previous data and in particular Figure I-15 allows a technique for estimating the frictional resistance of the hull of a steel icebreaker.

4.8.1 Regime I

Under those conditions where ice is being moved (free ice floating in water) pressures will be low, certainly less than 100 psi and a constant coefficient of friction can be selected depending upon the velocity of the ship.

For example, for steel:

Stopped	$f = 0.85$
Moving with a velocity $< .5$ mph	$f = 0.30$
Moving with a velocity $> .5$ mph	$f = 0.12$

For another surface material, each of these values would be different depending upon the following:

hull roughness
ice temperature
velocity.

The hull roughness can of course be measured but the ice temperature will vary with the ambient temperature. How much this varies in practice is unknown and must be determined by actual field measurements.

Under these conditions the frictional resistance of the hull

$$F_s = a_h S \text{ (pounds)} \quad \begin{array}{l} a_h = \text{area involved} \\ S = \text{surface shear stress} \end{array} \quad (4)$$

can be estimated by substituting

$$f = \frac{S}{P_{xy}} \text{ (definition of friction coefficient)}$$

in Eq.(4) yielding

$$F_s = a_h f P_{xy}.$$

Using this equation the selected friction coefficient is substituted for f and the pressure P_{xy} is estimated at each point on the hull. Milano (Ref.8) reviews the methods for determining ice pressures on the hull. P_{xy} and a_h will have to be estimated for each ice condition.

4.8.2 Regime II

Where the ice field is subject to constraints, the ice will be broken or crushed and high pressures (100 psi) will result. Under the conditions it is not necessary to estimate the pressure since the friction shear stress S is constant - S^* . The hull frictional resistance is then estimated as:

$$F_s = S^* a_h \text{ pounds}$$

where a_h is the area of the hull involved and S^* is a function of the same variables as the friction coefficients of low pressure friction. For the conditions of Figure I-18 (steel, 130 CLA, and -20°C [-4°F]) S^* is 35 psi for static friction and 14 psi for kinetic. Under these conditions it is necessary to estimate the area of the ship a_h , which is involved in each type of ice-breaking. This can only be obtained by experimental observation.

The question to be answered in this report then becomes how to determine viable f and S^* values. Since the friction coefficient obtained in the sled tests appear to be similar to those obtained in sled and model tests it is felt that a bench test (as used in these studies) is adequate if proper attention is paid to controlling the important variables.

Referring to Figure I-8 it can be seen that the coefficient of friction at 100 psi can be used to determine both f and S^* . At 100 psi, $f = 0.14$ for the ice moving condition and $f_p = 14 \text{ psi} = S^*$ for the icebreaking condition. These experiments are only needed at one pressure. The materials used of course and their roughness must be the same as that of the hull. Thus it is only necessary to obtain the friction coefficient at 100 psi over a variety of temperatures. These data are shown in Figure I-4 for two different roughnesses and this data can be applied directly to the ship if the ice temperature in icebreaking can be estimated.

Thus it can be seen that the frictional resistance of the hull of an ice-breaker can be determined from bench test experiments provided that the ice-breaking temperature and the area of the hull involved can be estimated for each icebreaking condition. This should be determined by experimental observation. However, further bench test data should be acquired to determine if the 100 psi bench test point applies to various roughnesses, temperatures, and materials. Further experiments are also needed to determine more accurately the water on ice friction coefficients.

4.9 Ice Testing Conditions

One of the major problems in establishing the frictional characteristics is knowing and establishing the testing conditions. An example of this is water on -1°C (31°F) ice will not give the same results as water on -20°C (5°F) ice. The difference is the strength of the ice underneath. In the -1°C case it is possible that the water will increase the surface temperature of the ice to its melting point making the ice unable to support any load. With the -20°C ice before the water freezes, the temperature of the ice underneath is low enough to support a substantial load and the water on the surface can form a lubricating film producing very low friction. Therefore, even though in both cases the water is on the surface, the strength of the ice underneath established the kinetic friction coefficient of the sliding surfaces.

It is particularly difficult to establish the properties of the ice outdoors since the surface condition of the ice is not controllable. Of particular importance is the ice condition if the sun is shining on the surface or if it is hidden by clouds, or if a wind is drying the ice surface. All of these seemingly minor instances could have a significant effect on the friction of a surface sliding against ice.

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Other parameters which should be established and recorded are:

1. Relative humidity
2. Velocity
3. Surface roughness
4. Ambient temperature
5. Temperature of the sliding surface
6. Other cover on the ice, i.e., snow, slush and conditions of the cover (hard packed, loose, etc.).

It is recommended that a complete survey of the weather which exists during ice friction testing evaluation be made to establish the condition of the ice surface. Observations such as a film of water on the surface, bright sunshine, shade, heavy wind, time of day, etc., will establish the condition of the ice surface. It is of course not possible to control these parameters but recording the conditions will help the experimentalist establish ice surface characteristics during testing.

SECTION 5

NEW MATERIALS

Several polyurethane coatings were selected as candidate materials for full-scale testing during the Phase I portion of this program (Ref.2). Of the materials tested a nonsolvented polyurethane (Zebron) showed the greatest promise.

Some new materials were obtained and evaluated in this phase of the program. These are:

- Slip plate - graphite filled alkyd coating manufactured by Superior Graphite Co.
- Slip plate - graphite filled epoxy coating manufactured by Superior Graphite Co.
- Polyurethane - chemical cure system containing approximately 25% solvent - manufactured by Advanced Coating & Chemicals
- Polyurethane - nonsolvented polyurethane - Urafilm - manufactured by Advanced Coatings and Chemicals
- Polyurethane - nonsolvented Zebron - same coating as applied and tested on the Cutter Raritan. The only difference is that this material does not have an amorphous silica filler - manufactured by Xenex Corporation.
- Hydrophilic material - a polymer manufactured by Hempel Marine Paints - used as an antifouling compound and a slip agent.
- Glass-filled polyester - Res-n-Glass - manufactured by Woolsey Marine Corporation.
- Epoxy - Marine coating manufactured by Woolsey Marine Corporation.
- FTE dry film - teflon filled epoxy applied to a sand blasted surface - manufactured by 3M Corporation.
- Urethane - elastomeric - nonsolvented - two part - chemical cure - urethane manufactured by 3M Corporation.

Polyurethane - nonsolvented - Conelcote - manufactured by Continental Coatings Corporation.

Epoxy - Inerta 160 - nonsolvented - two part epoxy - manufactured by Teknos Maalit Oy - Helsinki, Finland.

The tests run were the abrasion test (Figure I-25) and the friction test, both described in the Phase I report (Ref.2). The abrasion test is a modified ore crusher which accepts coated test specimens. Essentially the test specimen is mounted on a plate which oscillates toward a stationary plate. Fifty pounds of ice chunks are introduced between the oscillating specimen and the stationary plate. The ice chunks fall through after they are crushed by the specimen. The gap between the oscillating and stationary plate is reduced and a second 50 lbs of ice is introduced. A schematic of the test rig is shown in Figure I-26.

The surface roughness of the coated specimens was measured before and after tests on a Talysurf-4 profilometer.

The results of the tests are shown in Table I-4. The graphite filled alkyd and epoxy both spall off the steel surface during the ice crushing. The original surface roughnesses were $140 \mu''$ - $180 \mu''$ CLA and both increased to over $400 \mu''$ during test. A second series of tests were run on this material using a heavier grit blast surface preparation. The coating again was removed during the test.

The 25% solvent polyurethane coating was rough after the test. The surface roughness was re-measured after the specimens were allowed to stand for two days. No decrease in roughness was noted after two days.

The Urafilm nonsolvented polyurethane appears to be very similar to the previous nonsolvented polyurethane tested in the Phase I report. The major difference is in the application techniques. When the coating was originally

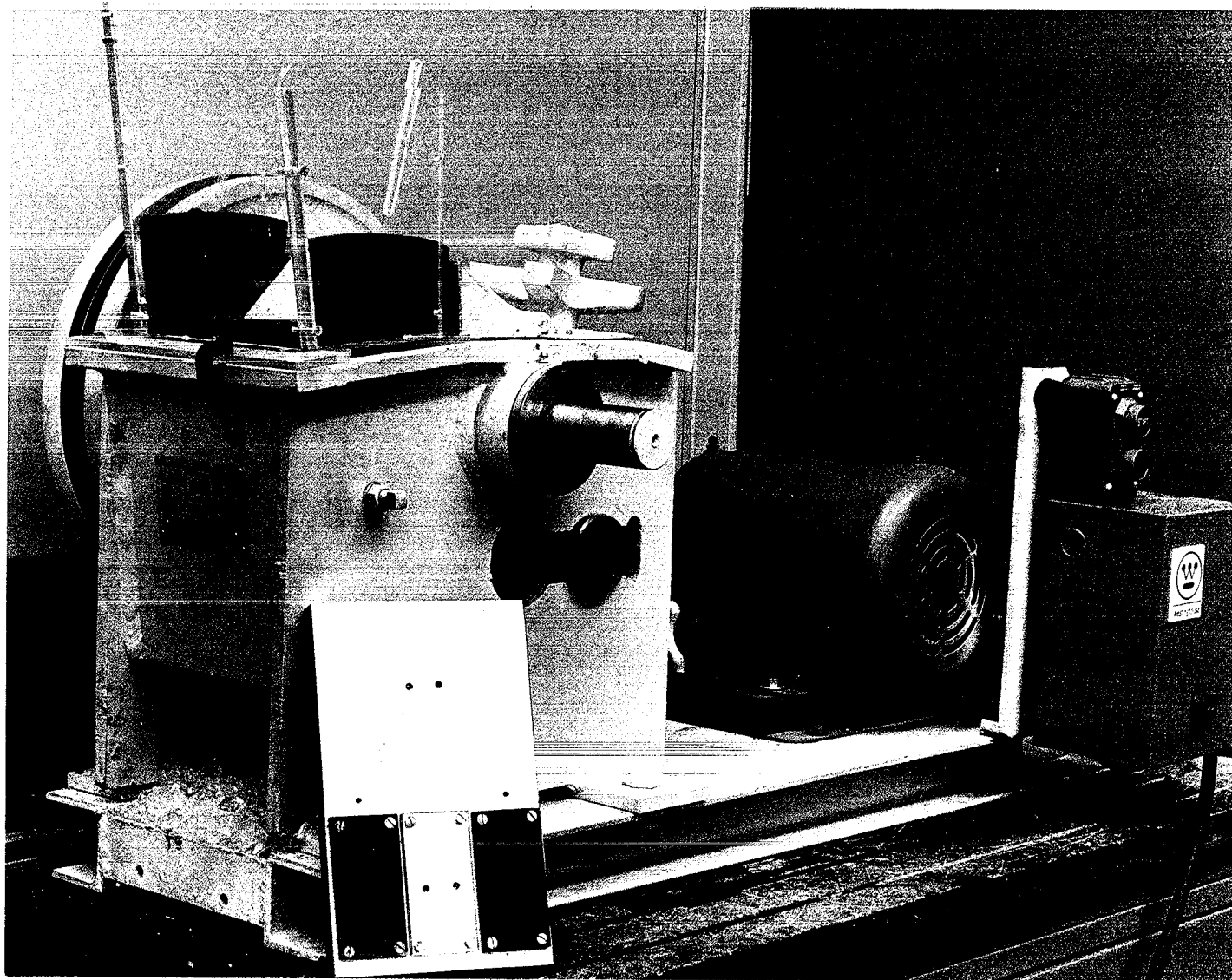


Figure I-25 Ice Crusher Test Used to Evaluate Various Materials for Ice Abrasion

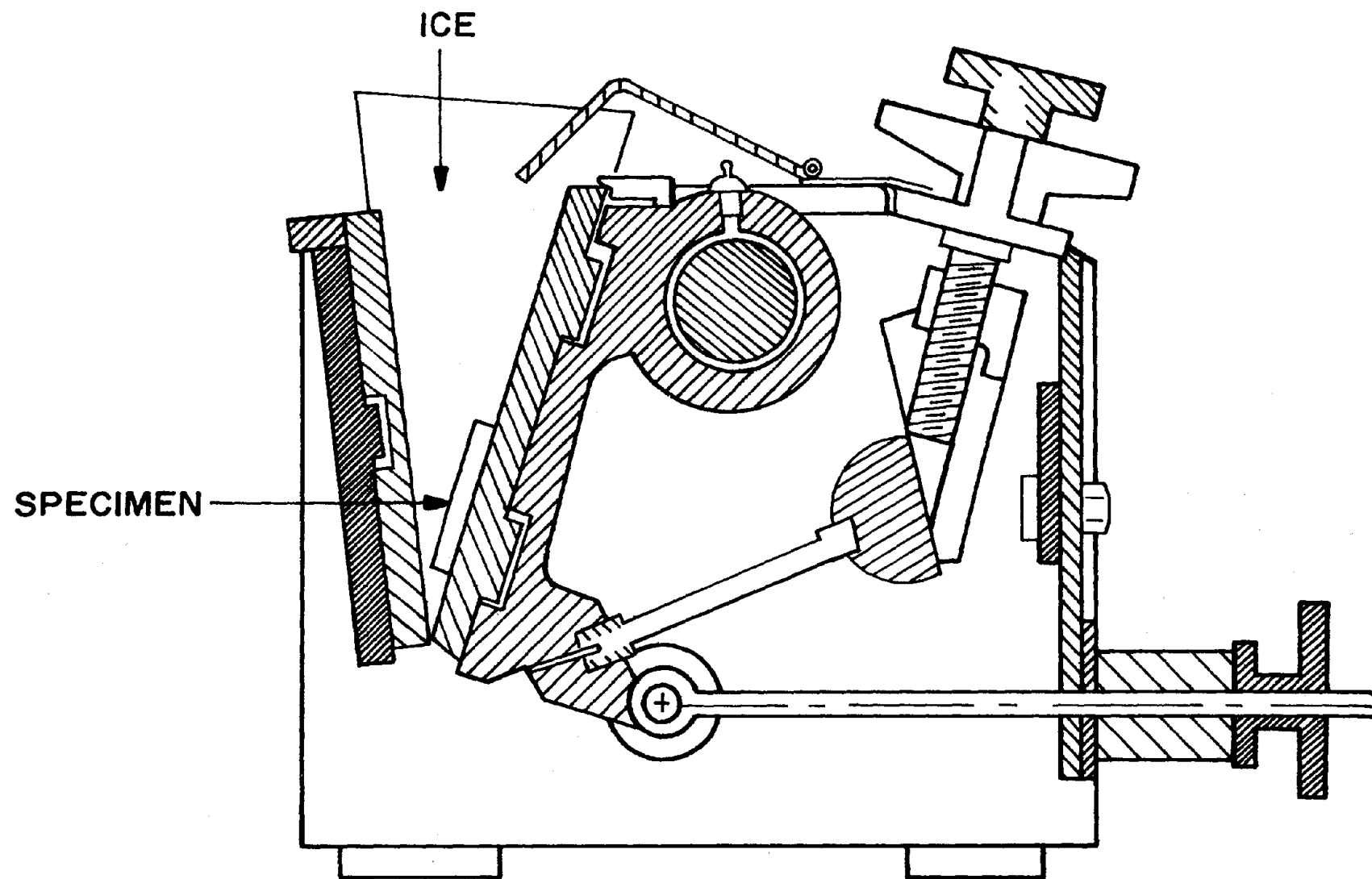


Figure I-26 Essential Parts of the Ice Crusher Test

TABLE I-4

RESULTS OF THE ABRASION TESTS RUN ON VARIOUS CANDIDATE COATINGS

Material	Brand Name	Surface Roughness		Thickness	Remarks
		Before Test μ'' CLA	After Test μ'' CLA		
Graphite filled alkyd	Slip plate	140.0	> 400.0	.006	Removed from the surface
Graphite filled epoxy	Slip plate	180.0	> 400.0	.006	Removed from the surface
Polyurethane 25% solvent	Advanced coating	33.0	50.0	.035 - .040	Heavy scratches, permanent damage
Polyurethane nonsolvented	Urafilm	70.0	80.0	.028 - .028	Very light scratches
Polyurethane nonsolvented unfilled	Zebron	80.0	85.0	.035"	Very light scratches
Hydrophilic polymer	Hydron Dynamics	40.0	150.0	.001"	Material was removed from the surface
Glass-filled polyester	Resin glass	350.0	280.0	.035"	Surface appears to be wearing
Epoxy	W-2	11.0	14.0	.010"	Very light scratches

TABLE I-4 (cont'd.)

Material	Brand Name	Surface Roughness		Thickness	Remarks
		Before test μ'' CLA	After test μ'' CLA		
FTE dry film	3-M -SBO	100 μ''	125 μ''	.0008" - .0010"	Light scratches
FTE dry film	3M-SBP	110 μ''	130 μ''	.0008" - .0010"	Light scratches
Urethane	3M-elastomeric	30 μ''	140 μ''	.018 - .020"	Surface deformed
Polyurethane	Conelcote	32 μ''	62 μ''	.035	Light pitting
Epoxy	Inerta 160	78 μ''	75 μ''	.016	No damage

received the surface roughness was greater than 400 μ " CLA. The surface had to be ground down to 70 μ " in order to produce a reasonable surface. The reason for the original higher surface roughness was due to the application equipment. Since the friction of materials sliding against ice is highly dependent on the surface roughness, it is important that the coating applied to the ship's hull be as smooth as possible.

The surface roughness increased slightly during the abrasion test. The values obtained were 70 μ " CLA before test and 80 μ " CLA after. Very light scratches were noted on the surface after test.

The Zebron nonsolvented polyurethane is the same coating as was originally tested under the trade name Crandalon. The only difference is that this material does not have amorphous silica as a filler. The coating is applied the same way as the filler material but has a finer surface finish. The crushing test showed that the surface roughness increased slightly for 80.0 μ " to 85.0 μ " CLA. Very light scratches were seen after the test.

The hydrophilic polymer was removed from the surface during the ice abrasion test. The surface roughness increased from 40 μ " to 150 μ ". The bond strength to the substrate was not adequate to withstand ice abrasion.

The glass-filled polyester (Res-n-glass) also had a very high surface roughness "as received". During the abrasion test the surface roughness reduced from 350.0 μ " to 280.0 μ ". Although the surface appears to be wearing, the coating shows little damage. The surface roughness of the coating in the "as applied" condition is 350 μ ". Some effort should be expended to reducing the surface roughness of this coating. The coating can be surface ground but that would mean expended effort and time when applying this coating to a large ship's hull.

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5.1 Conclusion

The materials which appeared to be most promising during the ice crushing test are:

1. Polyurethane - nonsolvented Urafilm
2. Polyurethane - nonsolvented Zebron (unfilled)
3. Epoxy - W2
4. Epoxy - nonsolvented Inerta 160.

5.2 Frictional Properties of the New Materials

Candidate materials which gave good results in the abrasion test were run on the friction test to measure their frictional behavior against ice.

The test rig is described in the previous report (Ref.2) but a brief description follows.

The coated test specimen is a ring 2" OD \times 1 1/4" ID \times 1/2" thick. The ring is held in a holder driven through dowel pins and a ball and socket arrangement mounted to a drill press head. The coated surface slides against a cup containing ice, held in an angular contact bearing supported housing. The housing is restrained by torque arms on which strain gages are mounted. The test rig is mounted in a cold box on the bed of the drill press.

The temperature is controlled by a thermocouple mounted in the ice cup. A low temperature refrigerating unit cools the test rig housing by means of coils around the test rig inside the cold box. Photographs of the test rig are shown in Figures I-6 and I-27. Figure I-27 shows the essential parts of the test rig and Figure I-6 shows the test setup.

The breakaway, static and dynamic friction were measured for each of the candidate coatings. The test conditions were as follows:

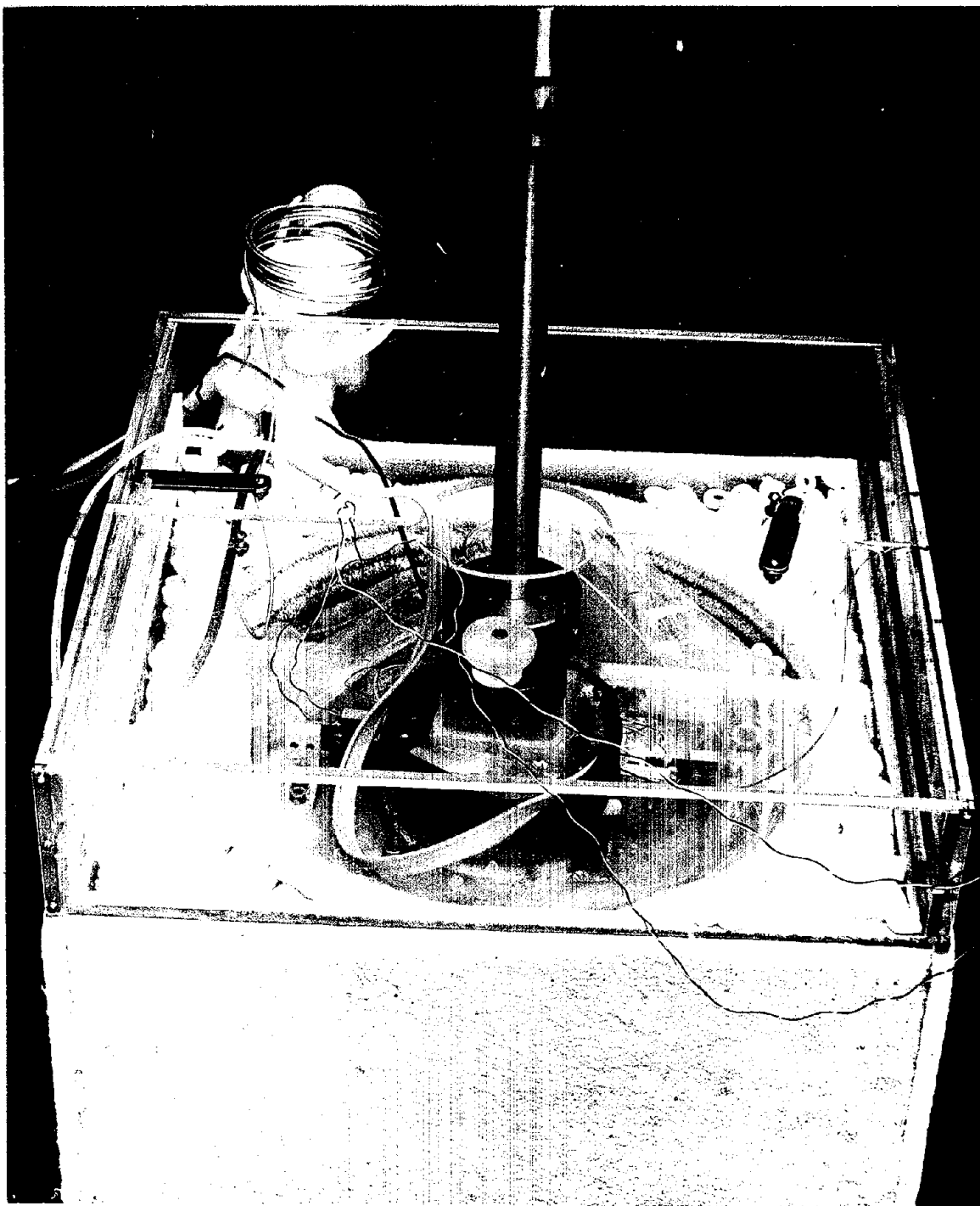


Figure I-27 Low Temperature Test Rig Used to Measure the Frictional Properties of Various Materials

- (a) Load - 30, 50, 90, 150 and 200 lbs.
- (b) Temperature - -22°C (-7°F).
- (c) Velocity - breakaway - .4" sec; static - .4" sec; kinetic - 283 ft min.
- (d) Environment - air.
- (e) Surface roughness - as indicated.

The test results (Table I-5) show the friction for the polyurethane with the 25% solvent system gave breakaway values which varied between .26 and .2. The static values varied between .12 and .16. The kinetic values were between .05 and .07. The material gave permanent damage due to heavy scratches.

The nonsolvented Urafilm gave high values for this type of system. The reason for this is because of the high surface roughness due to application techniques. Since this material appears to be very similar to the nonsolvented coating used in the Phase I part of the program, different application equipment which improve surface roughness should reduce the frictional properties significantly.

The unfilled polyurethane (Zebron) gave results similar to the filled coating.

The glass filled polyester gave high friction values throughout the test.

The epoxy gave frictional values varying between .23 for breakaway to .08 kinetic.

Conelcote and Inerta 160 friction specimens were not available. Continued effort will be placed on both materials to determine their friction properties and bond strength properties.

TABLE I-5

FRICTIONAL BEHAVIOR OF COATING MATERIALS

CIA

Material	30 lbs			50 lbs			90 lbs			150 lbs			200 lbs			Before Test (μ'')	After Test (μ'')
	Breakaway	Static	Kinetic	Breakaway	Static	Kinetic	Breakaway	Static	Kinetic	Breakaway	Static	Kinetic	Breakaway	Static	Kinetic		
Polyurethane 25% Solvent	.2	.12	.06	.26	.14	.05	.24	.14	.07	.21	.15	.06	.22	.16	.06	35.0	80.0
Polyurethane Nonsolvented (Urafilm)	.21	.14	.08	.23	.11	.07	.24	.14	.06	.24	.15	.06	.25	.16	.05	250.0	250.0
Polyurethane Nonsolvented Unfilled (Zebron)	.12	.10	.04	.11	.11	.03	.11	.11	.04	.11	.11	.04	.12	.11	.04	75.0	75.0
Glass Filled Polyester (Res-n-glass)	.35	.16	.1	.38	.16	.12	.35	.16	.12	.36	.17	.11	.37	.16	.11	350.0	210.0
Epoxy (W-2)	.20	.10	.1	.21	.10	.1	.23	.13	.1	.21	.1	.09	.2	.09	.08	10.0	11.0

5.2.1 Results

Of those materials on which laboratory testing was employed, the unfilled Zebron gave the best results from both abrasion resistance and low friction. Other materials gave either poor bonding, surface damage and lack suitable surface roughness to produce low friction.

SECTION 6

COATING APPLICATION STUDY

Most coating manufacturers have application procedures which they recommend for their coatings. The procedures usually recommend the surface preparation, application equipment, temperature, humidity, thickness, cure time, etc.

In almost all cases the coating procedure can be strictly followed. The only exception is the weather conditions. Ship coating is normally done at a dry dock, outdoors, near a body of water. Large amounts of dust or grit can become airborne due to grit blasting on a nearby ship. The airborne particles can deposit on a newly painted surface. Heavy gusts of wind carry particles to a ship containing a paint coating which is still tacky. Flash storm deposits rain or moisture on the hull in between coats. Rain or fog may occur during the evening hours while a coating is still curing on which subsequent coatings must be applied. Mishaps occur which could deposit large amounts of debris to the hull.

Any or all of the above conditions may occur while coating a ship's hull. These may or may not be detrimental to the coating. Accordingly, a study was conducted to determine the effect of application parameters for some typical hull coatings. The coatings were applied in an environment similar to a dry dock.

The materials tested were as follows:

- a) Polyamide epoxy primer
- b) Wash primer (polyvinyl butyral + phosphoric acid)
- c) Zinc rich epoxy primer
- d) Coal-tar epoxy
- e) Vinyl antifoul

- f) Polyamide epoxy high build
- g) Rigid polyurethane (moisture cure) one part system
- h) Elastomeric polyurethane (chemical cure) two components.

The coating was applied to test coupons 1 1/2" square by 1/4" thick. The surface of the steel specimen was prepared by grit blasting with S_iO_2 grit (coarse grade). The base coat was applied immediately after grit blasting. Each set of specimens were coated from the same batch of material.

Application was accomplished with a conventional air type spray gun, outdoors and allowed to cure under several curing conditions. The curing conditions were as follows:

- a) Outdoors under normal weather conditions
- b) Indoors at 21°C (70°F), 30% relative humidity
- c) 37.8°C (100°F) oven.

After curing, tensile grips were epoxied to the coated surface and then pulled from the test specimen. The stress applied to the coating was measured and recorded. A complete description of the test fixtures used is given in the previous report (Ref.2).

The temperature, humidity and weather conditions during application and curing were measured and recorded. The coating system applied and curing position is as follows:

Series 1

- Specimen 1A - Polyamide epoxy primer - base coat
Polyamide epoxy high build - middle coat
Polyamide epoxy top coat -
Room temperature cure.
- Specimen 1B - Same as above.
Outdoor cure.
- Specimen 1C - Same as above.
Oven cure.

Series 2

Specimen 2A - Polyamide epoxy primer - base coat
Anti-corrosion - middle coat
Vinyl antifoul - top coat
Room temperature cure.

Specimen 2B - Same as above.
Outdoor cure.

Specimen 2C - Same as above.
Oven cure.

Series 3

Specimen 3A - Zinc rich epoxy primer - base coat
Anti-corrosion - top coat
Room temperature cure.

Specimen 3B - Same as above.
Outdoor cure.

Specimen 3C - Same as above.
Oven cure.

Series 4

Specimen 4A - Inorganic zinc - base coat
Coal tar epoxy - top coat
Room temperature cure.

Specimen 4B - Same as above.
Outdoor cure.

Specimen 4C - Same as above.
Oven cure.

Series 5

Specimen 5A - Zinc chromate polyamide epoxy primer - base coat
Polyurethane rigid moisture cure - top coat
Room temperature cure.

Specimen 5B - Same as above.
Outdoor cure.

Specimen 5C - Same as above.
Oven cure.

Series 6

Specimen 6A - Zinc chromate polyamide epoxy primer - base coat
Polyurethane elastomer - chemical cure - middle coat
Polyurethane rigid moisture cure - top coat
Room temperature cure.

Specimen 6B - Same as above.

Specimen 6C - Same as above.
Oven cure.

Table I-6 shows the coating conditions, curing conditions and the fracture values obtained during tensile testing. The coating used refers to the above series number.

The results are as follows:

Series 1 - A significant increase in bond strength was noted on the specimens cured in the oven. All specimens separated between the primer and the middle coat.

Series 2 - The specimens cured outdoors and indoors separated at the bond between the antifoul top coat and the anti-corrosion middle coat. The oven cured specimens separated in the antifoul coating - cohesive failure.

Series 3 - The poorest values obtained were on the specimens coated and cured outdoors. The coating cured indoors gave a slight increase and the specimens cured at 100°F gave a still greater increase in strength.

TABLE 1-6

Specimen # -		1A	1B	1C	2A	2B	2C	3A	3B	3C	4A	4B	4C	5A	5B	5C	6A	6B	6C
1st Coat	Application Temperature and Humidity	73°F	73°F	73°F	73°F	73°F	73°F	73°F	73°F	73°F	73°F	73°F	73°F	81°F	81°F	81°F	81°F	81°F	81°F
	Cure Temperature and Humidity	72°F	64°F	100°F	72°F	64°F	100°F	72°F	64°F	100°F	72°F	64°F	100°F	72°F	65°F	100°F	72°F	65°F	100°F
		30%	90% rained		30%	90% rained		30%	90% rained		30%	90% rained		30%	65%		30%	65%	
2nd Coat	Application Temperature and Humidity	88°F	88°F	88°F	81°F	81°F	81°F	81°F	81°F	81°F	88°F	88°F	88°F	79°F	79°F	79°F	77°F	77°F	77°F
	Cure Temperature and Humidity	71°F	64°F	100°F	71°F	65°F	100°F	70°F	65°F	100°F	65°F	64°F	100°F	72°F	62°F	100°F	72°F	58°F	100°F
		28%	75%		28%	65%		26%	65%		65%	75%		28%	75%		28%	75%	
3rd Coat	Application Temperature and Humidity	74°F	74°F	74°F	88°F	88°F	88°F										79°F	79°F	79°F
	Cure Temperature and Humidity	72°F	62°F	100°F	72°F	64°F	100°F										72°F	62°F	100°F
		30%	70%		30%	75%											30%	70%	
Fracture Pressure (psi)		535	503	733	210	146	284	484	497	497	597	574	1712	828	625	1012	607	586	516
		Indoor Cure	Outdoor Cure	Oven Cure	Indoor Cure	Outdoor Cure	Oven Cure	Indoor Cure	Outdoor Cure	Oven Cure	Indoor Cure	Outdoor Cure	Oven Cure	Indoor Cure	Outdoor Cure	Oven Cure	Indoor Cure	Outdoor Cure	Oven Cure
		Broke between primer & middle coat.	Broke between primer & middle coat.	Broke between primer & middle coat.	Broke between antifoul & anti-corrosion coat.	Broke between antifoul & anti-corrosion coat.	Broke in the antifoul coat.	Broke in the anticorrosion coat.	Broke in the anticorrosion coat.	Broke in the anticorrosion coat.	Broke in the coal tar epoxy coat.	Broke in the coal tar epoxy coat.	Broke between the coal tar and primer coat.	Broke between the metal substrate and primer coat.	Broke between the metal substrate and primer coat.	Did not damage the coating. Broke in the fixturing epoxy.	Broke between the elastomer and topcoat.	Broke between the elastomer and topcoat.	Broke between the elastomer and topcoat.

Series 4 - The specimens cured indoors and outdoors gave similar results. Both gave a cohesive failure in the coal tar epoxy. The specimens cured at 100°F gave very high strength values and an adhesive failure was noted between the coal tar epoxy and the inorganic zinc primer.

Series 5 - The specimens coated with the rigid polyurethane gave the lowest values when applied and cured outdoors. The coating cured indoors gave higher values and the coating cured at 100°F gave the highest values.

Series 6 - All specimens gave similar values and all broke at the interface between the elastomer and the rigid polyurethane.

6.1 Conclusions

Under the conditions tested, there appears to be little difference between applying and curing an epoxy coating outdoors or indoors. Most of the epoxy type coatings show an improvement in bond strength when cured at 100°F (38°C).

Little differences were seen with the elastomer polyurethane when cured outdoors or indoors but a significant increase was seen with the rigid urethane system. The oven cured rigid urethane gave an even greater increase in bond strength and again little significant difference was seen with the elastomeric urethane when oven cured.

A second series of tests should be run at lower application and curing temperature for a more complete evaluation.

6.2 Effect of Surface Cleaning

A second series of tests were run on a polyurethane system and an epoxy system. Two specimens were coated with the same system and allowed to cure during poor weather conditions. The specimens were allowed to set out over night in the rain and subsequent coatings were applied on top. One of each set of specimens was cleaned with a solvent (reagent grade Toluene) after exposure to the rain. The second specimen was coated without cleaning.

The purpose of the test was to determine

- a) What effect moisture deposited on a partially cured surface would have.
- b) Should a ship which had been partially coated and exposed to rain be solvent cleaned before subsequent coats are applied.

The specimens used were the same as those described in the previous test.

The coatings selected were:

- | | |
|-------------------|---|
| Coating System I | A Polyamide epoxy primer containing chromates
base coat |
| | B Polyamide epoxy high build - middle coat |
| | C Polyamide epoxy top coat - top coat |
| Coating System II | A Wash primer - modified polyvinyl butyral resin
and phosphoric acid catalyst base coat. |
| | B Polyurethane elastomer chemical cure - middle coat |
| | C Polyurethane - rigid - moisture cure. |

All of the above are systems used for marine coating application.

The coating steps and conditions were as follows:

Spec. 1A & 1B Polyurethane System

	Application Temp.	Humidity	Cure Temp.	Humidity
1. Grit blasted all surfaces				
2. Applied wash primer	77°F	72%	58°F	75%
3. Allow to set in rain overnight				
4. Clean B spec. with Toluene				
5. Apply Elastomer	89°F	83%	73°F	60%
6. Apply rigid topcoat	79°F	65%	62°F	70%

Spec. 2A and 2B Polyurethane System

	Application Temp.	Humidity	Cure Temp.	Humidity
1. Grit blasted all surfaces				
2. Apply wash primer	77°F	72%	58°F	75%
3. Apply Elastomer	89°F	83%	73°F	60%
4. Allow to set in rain overnight				
5. Clean B spec. with Toluene				
6. Apply rigid topcoat	79°F	65%	62°F	70%

Spec. 3A & 3B Polyurethane System

	Application Temp	Humidity	Cure Temp.	Humidity
1. Grit blast all surfaces				
2. Apply wash primer	77°F	72%	58°F	75%
3. Apply Elastomer	89°F	83%	73°F	60%
4. Apply rigid topcoat	79°F	65%	62°F	70%
5. Allow to set in rain overnight				
6. Clean B spec. with Toluene				
7. Apply rigid topcoat	82°F	75%	64°F	75%

Spec. 4A & 4B Polyamide Epoxy

	Application Temp.	Humidity	Cure Temp.	Humidity
1. Grit blast all surfaces				
2. Apply polyamide primer	88°F	80%	73°F	60%
3. Allow to set in the rain				
4. Clean B spec. with Toluene				
5. Apply polyamide middle coat	83°F	75%	64°F	70%
6. Apply polyamide topcoat	86°F	78%	70°F	83%

Spec. 5A & 5B Polyamide Epoxy

	Application Temp.	Humidity	Cure Temp.	Humidity
1. Grit blast all surfaces				
2. Apply polyamide primer	88°F	80%	73°F	60%
3. Apply polyamide middle coat	83°F	75%	64°F	70%
4. Allow to set in the rain				
5. Clean B specimen only with Toluene				
6. Apply polyamide topcoat	86°F	78%	70°F	83%

Spec. 6A & 6B Polyamide Epoxy

	Application Temp.	Humidity	Cure Temp.	Humidity
1. Grit blast all surfaces				
2. Apply polyamide primer	88°F	80%	73°F	60%
3. Apply polyamide middle coat	83°F	75%	64°F	70%
4. Apply polyamide topcoat	86°F	78%	70°F	83%
5. Allow to set in the rain				
6. Clean B spec. only with Toluene				
7. Apply second topcoat	83°F	65%	65°F	70%

It should be noted that the values of humidity reported during curing are the values obtained most of the curing period. During the time when it rained, the humidity was of course 100%. The bond strength values obtained are shown in Table I-7.

TABLE I-7

Specimen #	Coating System	Strength Values (psi)		Remarks
1A	Polyurethane	755		Broke in the elastomer
1B	Polyurethane	739		Broke in the primer
2A	Polyurethane	670		Broke in the elastomer
2B	Polyurethane	709		Broke in the elastomer
3A	Polyurethane	650		Broke in the elastomer
3B	Polyurethane	610		Broke in the elastomer
4A	Epoxy	523		Broke in the primer
4B	Epoxy	233		Broke in the primer/middle
5A	Epoxy	509		Broke in the primer
5B	Epoxy	357		Broke in the middle/ topcoat bond
6A	Epoxy	593		Broke in the primer
6B	Epoxy	327		Broke in the topcoat

No significant change in bond strength was seen with the polyurethane coating. With the epoxy coating the specimens which were cleaned with Toluene gave a significant reduction in bond strength. This is very surprising since Toluene is a solvent which is sometimes used as a brush cleaner for epoxy paints. However, in every case the specimen cleaned with Toluene gave lower values than the specimen which was not cleaned.

6.2.1 Conclusions

Little difference was seen between polyurethane coated surfaces cleaned with Toluene or not cleaned after exposure to precipitation while curing.

After cleaning exposed epoxy coated surfaces with Toluene, a significant drop in bond strength was noted. Other solvents (MEK, Xylene, acetone) can be used as cleaning agents and should be evaluated in this manner.

6.3 Improved Surface Conditions

The surface roughness of materials sliding against ice has been shown to be an important factor in ice friction. For any given material the friction coefficient can be increased or decreased by changing the surface roughness. Icebreaker hulls are normally rough due to the corrosion, pitting welds and damage sustained during icebreaking. The smooth hull plating is approximately 400 μ " CLA. With additional corrosion, pitting, welds and so forth it is possible to get an overall average profile of .050" CLA

Several methods may be used to improve the surface roughness. They are as follows:

- (a) grind the steel plates smooth
- (b) apply (spray) coating material and grind off the asperities
- (c) apply putty into the pits and grind smooth
- (d) apply (spray) a high viscosity coating material and squeegee while wet.

Grinding the steel plates smooth is not practical since some of the pits are very deep and would weaken the hull considerably. Also, the manpower needed for grinding the hull would be prohibitive.

Applying (spraying) a coating and grinding the asperities would also be extremely expensive since several coats would have to be applied and allowed to cure before each successive grind and recoat. This process is used by many automobile and furniture manufacturers. They apply the coating, cure and sand (or grind) the surface. A second coat is applied and re-sanded, etc. The pores in the surface are filled with coating material and then the final coat is applied and cured. This process is effective on a surface which has small imperfections but would take several man hours to accomplish on a surface with heavy surface damage and pits such as seen on an icebreaker hull.

Applying putties is a process which is now used on some ships in order to fill in severely pitted areas. This is also very expensive since the putty is applied by hand trowelling over a small area.

The last method suggested is to apply a high viscosity spray coating to the hull and immediately "squeegee" the surface while the coating is still wet. After curing minor grinding can be done in areas where the coating build up is too high.

The primer is recommended to reduce the hull roughness because the addition of particles to the surface coating might change the frictional properties of the coating. This process can only be done if the primer coat can be applied at thickness above 2 mils. Many primer manufacturers recommend a dry film thickness of less than .001 mil. This is especially true with wash primers. The addition of a thickening agent is not recommended for these materials.

Many of the primer coatings used for underwater marine applications are zinc rich polyamide epoxies. An attempt was made to add a thickening agent to

the primer in order to apply them to specimens containing large voids (pits). The void would be filled with material and the surface squeegeed.

Several materials were used as thickening agents, they are:

<u>Material</u>	<u>Particle Size</u>
1. Aluminum oxide	17 microns
2. Aluminum and magnesium silicate	44 to 74 microns
3. Aluminum metal powder	40 microns
4. Silica (SiO_2) (several grades)	150, 45, 20, 5, .5 microns
5. Collodial silica	

Aluminum oxide, aluminum magnesium silicate and aluminum powder would not stay in suspension long enough to allow the coating to be applied easily. The viscosity of the fluid varied drastically from the top of the fluid to the bottom. Continuous agitation kept the particles suspended more uniformly but after applying this to the surface the coating produced a very rough, non-uniform finish.

The large silica powder (150 microns) produced the same results as the above. Smaller particles stayed in suspension but appeared to increase the viscosity drastically in a very short period of time. The coating was not pourable in a matter of a few minutes and had to be trowelled on the surface.

The collodial silica gave the most promising results. A 1.5% mixture (by weight) was the maximum proportion which could be sprayed at 50 psi. A 3 to 5% mixture had to be trowelled on the surface and is most effective in filling large pits.

Other application techniques such as rolling or brushing were less effective.

- Application by brush does fill the pits but because of the increased viscosity, flow is restricted during curing and the brush strokes become evident. Therefore the surface roughness is determined by the brush marks.
- Application by roller fills the pits but bubbles result as the trailing edge of the roller leaves the surface. The increase in viscosity will not allow the coating to flow and therefore the bubbles remain while the coating sets up. The applied coating is distributed unevenly on the surface causing an unacceptable surface roughness value.

A series of tests were run with a sprayable mixture, to determine the characteristics of the coating. The coating was applied as follows:

- (a) Spray gun and compressor - 1 hp - external mix nozzle - spray pressure 50 psi.
- (b) Mixture of collodial silica and polyamide epoxy primer.
- (c) Environment outdoors - spray and cure condition as indicated.
- (d) Steel test specimen - several blind holes were drilled in the surface to simulate large pits.

The coating was applied outdoors near the Hudson river to simulate a dry dock environment. It was sprayed with a conventional air type spray gun. An external mix nozzle at a pressure of 50 psi was used. The power source was 1 hp air compressor with a holding tank.

The temperature and humidity conditions during spraying and curing were measured and recorded. The coating was applied to 2" x 4" x 1/4" thick steel test specimen in which blind holes had been drilled to simulate large surface pits. A two part (resin and converter) polyamide epoxy primer was used with the collodial silica. All specimens were sprayed in a vertical position to determine if the coating would run out of the holes after spraying.

The following observations were made.

- Two grams of colloidal silica and 211 grams of epoxy gave a sprayable consistency at 17°C (62°F).
- Three grams colloidal silica and 204 grams of epoxy was a sprayable consistency at 62°F.
- Four grams colloidal silica and 208 grams of epoxy was not sprayable at 62°F. The spray gun nozzle plugged up.

Samples were sprayed in a vertical position to determine the amount of material that could be applied before the coating ran. Thirty-five mils of coating was applied to a vertical surface before any signs of running were noted.

A set of specimens were coated and the surface squeegeed to determine the amount of fill left in the holes and the number of times a coating had to be applied before the holes were completely filled. Three applications and squeegee procedures had to be made before the holes could be filled. All spraying was done on specimens in a vertical position. After the third application only one drilled hole was still detectable visually. The rest were completely filled with coating.

6.3.1 Effect of Curing Time

The addition of colloidal silica did retard the curing action of the polyamide primer. A batch of primer was mixed and sprayed on a specimen with no silica added. Colloidal silica was added to the same batch and sprayed. Additional converter was added to the epoxy to determine if it would decrease the reaction time. The results are shown in Table I-8. The term cure time does not refer to the length of time before subsequent layers can be applied but the amount of time to reach a predetermined hardness.

Curing time was established by a scratch test. When the coating would not scratch with E3 lead it was said to be cured. The epoxy primer used was a two-part system with a mixture ratio of three parts resin to one part converter. The addition of 3 grams of silica to 242 grams of primer lengthened the cure time from 16 hrs to 48 hrs under outdoor curing conditions. Even indoors the curing time was 24 hrs. The coating cured in 10 hrs when placed in an oven at 100°F (38°C).

No significant change in bond strength was noted. All values were between 480 and 620 psi.

6.4 Results

It appears that the polyamide epoxy primer does not significantly change when adding colloidal silica. However, the reaction time was increased three fold indicating a longer time period would be needed before the next coat could be applied. The overall strength and hardness was achieved after complete cure.

6.5 Conclusions

The addition of colloidal silica to a primer system (epoxy) reduced the surface roughness of a simulated pitted surface. The processes were accomplished by spraying and immediately squeegeeing the surface layer off. It is then repeated until pits are filled. Then subsequent top layers are applied. The addition of silica increases the length of time needed for curing, but final cure does occur.

The time delay will mean an additional expense in coating a hull. Therefore a potential user will have to decide the cost benefit depending on the following:

- a) Condition of the hull
- b) Length of time the ship will be in dry dock for other tasks.

TABLE I-8

Primer (grams) Resin Converter		Collodial Silica	Curing Condition	Curing Temperature Variation	Relative Humidity	Coating Bond Strength (psi)	Curing Time*
182	60	0	Outdoors	62°F(16.7°C) and 50°F(10.0°C)	30% to 60%	580	16 hrs
182	60	3 grams	Outdoors	62°F(16.7°C) and 50°F(10.0°C)	30% to 60%	580	48 hrs
182	60	3 grams	Indoors	70°F (21°C)	30%	480	24 hrs
182	70	3 grams	Outdoors	62°F(16.7°C) and 50°F(10.0°C)	30% to 60%	520	48 hrs
182	70	3 grams	Indoors	70°F (21°C)	30% to 60%	540	24 hrs
182	60	3 grams	Oven cure	100°F(37°C)	20%	620	10 hrs
182	60	2 grams	Outdoors	62°F(16.7°C) 50°F(10.0°C)	30% to 60%	510	48 hrs
182	60	2 grams	Indoors	70°F (21°C)	30%	500	24 hrs
182	60	2 grams	Oven cure	100°F(37°C)	20%	530	8 hrs

The economics of using a filled coating to reduce surface roughness could be beneficial depending on the condition of the hull. If the hull is not severely pitted, the benefits will be less significant.

The benefit will be realized in the following manner:

1. Coating life should be extended since no sharp pit edges exist where the coating can be chipped.
2. Reduction in friction in both ice and open water (Ref.3) resulting in a reduction in hull resistance.

It should be noted that the process of applying the coating and squeegeeing the surface was performed during the summer of 1975 on the USCG Cutter Mackinaw to reduce the hull surface roughness. The process is described in the Part II portion of this report. A significant reduction in surface roughness was realized by the squeegee process without an extended period of loss time. The coating applied was the nonsolvent polyurethane and in this instance the polyurethane was used to fill the pits. This is because the material is high viscosity without the need for a filler coat and a heavy coating could be applied without running or dripping.

PHASE II

PART II

FULL-SCALE TESTING

FULL SCALE TESTS

PHASE II

PART II

SECTION 8

A ship evaluation program was initiated in Phase I and continued into Phase II. In this program the best coatings, as they were isolated from the bench tests, were applied to the hull of an icebreaker and periodically examined during the icebreaking season. The results reported herein contain evaluations of ships coated and used for icebreaking during the winter of 1974, and a description of the coatings to be evaluated during the '75 winter season.

8.1 Candidate Coatings

Based on laboratory evaluations in Phase I, five coatings were selected as candidate materials for application to the hull of an icebreaker. All but one of these materials were polyurethane coatings but had different physical properties. A modified polyphenylene oxide coating was also selected. All of these materials exhibited low friction against ice, could be applied and cured under ambient outdoor conditions, gave low surface damage and produced low wear from crushing ice in the laboratory bench test.

The most important unknown was the bond strength values of the coating/undercoat system to the steel hull. Since it is very difficult to determine the stress on the hull due to icebreaking, the bond strength values are unknown and had to be determined by service testing. Hence the need for full-scale testing.

The urethane systems selected were different generic bases and different hardnesses.

8.2 Types of Polyurethane

Standard coating systems can be divided into five types; they are as follows:

100

1. Oil modified
2. Moisture cure
3. Blocked isocyanate
4. Prepolymer plus catalyst
5. Two component.

A urethane system forms as a result of the linkage between polyol and isocyanate (NCO). The means of reacting them determines the type or above category it falls into.

Type 1 - Oil modified urethanes are essentially the addition of the isocyanate resin to drying oil such as linseed or soybean oil. This is the type of material usually sold as polyurethane paints. They can contain as little as 3% urethane and are not the coating materials sold for industrial use.

Type 2 - The moisture cure types are unreacted isocyanate groups that react with the moisture in the atmosphere. They usually need at least 20% humidity to cure within a reasonable time period. Humidity higher than 20% is advantageous.

Type 3 - Blocked isocyanate coatings are materials containing the isocyanate groups which are blocked from reacting until heat is applied to them. They are essentially one-component systems needing heat for curing.

Type 4 - The prepolymer + catalyst type is very similar to the moisture cure except it has a catalyst added to accelerate the reaction with the atmospheric moisture. The major difference between this and Type 2 is that the Type 2 reaction with atmospheric moisture begins immediately upon opening the container.

Type 5 - The two-component system is a polyurethane system where component I is the polyol and component II is an isocyanate. These materials can be either aromatic or aliphatic. The aromatics are materials which can be rigid or

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flexible and exhibit very good chemical and abrasive wear resistance. They have poor resistance to discoloration due to weathering. The aliphatic urethanes were developed to have the same physical properties as the aromatic but also resist weather discoloration.

A sixth type of urethane is also available which is a hybrid of the above systems. It contains no solvent, can cure at room temperature, is flexible and exhibits good wear characteristics. This material has been evaluated in this program and the results will be discussed later.

The materials selected for full-scale testing are as follows:

- Rigid polyurethane - Dexter Corp. - Marine Midland - two-part chemical cure.
- Elastomeric polyurethane - Goodyear Corp. - two-part moisture cure.
- Rigid polyurethane - Chemglaze II - Hughson Chemical - moisture cure - one part.
- Elastomeric polyurethane - Hughson Chemical - two-part chemical cure.
- Elastomeric polyurethane - Zebron (formerly Crandalon) Xenex Corp. - two-part chemical cure - hybrid nonsolvent.

An evaluation of the full-scale testing follows.

SECTION 9

Coating Measurements During Application

During the coating application, test specimens and certain physical properties of the coating were obtained at the dry dock site.

The purpose was to obtain data on the specific coating being applied to the hull using the same equipment, application conditions and curing environment as the coating applied to the hull.

The properties examined are:

1. Bond strength (adhesion of the primer/topcoat system to the substrate). The bond strength properties were taken as measurement

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of the tenacity of the coating systems to the steel hull. The stress was applied in tension at 90° to the steel substrate. It is used for comparative purposes only. The stress is normally applied in shear on the hull of an icebreaker but the coating can be removed as a result of abrasion, peel or shear. The shear strength of a coating system is usually $1/3$ to $1/4$ of the tensile strength. Therefore knowing the tensile strength will give an indication of shear strength.

2. Application and curing conditions.
3. Coating thickness.
4. Surface roughness.
5. Tensile strength (cohesive strength).
6. Hardness.
7. Surface conditions (overall surface appearance before and after the ship has seen icebreaking service).

A more detailed discussion of the procedure used is given in Ref.2. The tests were taken and evaluated as follows:

1. Bond strength - steel test coupons $1\ 1/2"$ sq by $1/8"$ thick, were grit blasted, primed and coated at various times during the application at dry dock. The specimens were left outdoors and allowed to cure with the hull coating. They were then returned to RPI and the coating was pulled from the surface in a tensile machine while measuring the stress on the coating during fracture. The failed surface was examined to determine if the coating had separated in the topcoat, primer or at the metal substrate. The location of failure was recorded along with the bond strength.

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2. Temperature and relative humidity were measured and recorded in the morning and afternoon during the coating application. The area of the hull being coated during that period was noted and a record of precipitation, wind or other weather conditions was made for the entire coating period.
3. The coating thicknesses at various areas on the hull were measured and recorded after each coat was applied.
4. Replicas of the hull surface were taken at the dry dock and recorded when returned to the laboratory.
5. Tensile specimens were taken by spraying the coating on a polyethylene surface and removing the cured film from the polyethylene. The film was then returned to the laboratory for strength measurements.
6. Hardness measurements were taken on the hull coating using a pencil lead technique described in Paint Testing Manual (Pencil Method).

It should be stressed that the above measurements were taken as a method of determining the physical properties of the coating during application.

New measurements would be taken after the ship had seen icebreaking service and compared with the originals. The purpose was to determine

- a) wear
- b) surface damage
- c) coating deterioration

during service.

SECTION 10

Test Results

During the Phase I (Ref.2) laboratory evaluation of various materials sliding against ice, several polyurethane coatings were selected as candidate coatings for icebreakers.

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Several icebreakers were coated with the candidate materials and evaluated after service. The ships coated were: 1) USCG Cutter Yankton - home port, Portland, Maine; 2) USCG Cutter Sauk - home port, Governor's Island, New York; 3) USCG Cutter Mackinaw - home port, Cheboygan, Michigan; 4) USCG Cutter Raritan - home port, Grand Haven, Michigan; 5) USCG North Wind - home port, Baltimore, Maryland. In addition, the following ship with a glass flake polyester coating was evaluated: USCG West Wind - home port, Milwaukee, Wisconsin. Although this coating was not a candidate from the laboratory tests, it was of interest because it had been applied to an icebreaker. Other ships were also coated with marine hull coatings and the results of their condition after service are reported. A tabulation of the ships, coating, results and pending results are as follows:

Ship USCGC	Coating System	Coating Mfg.	Year Coated	Results
Yankton	Polyurethane elastomer	Goodyear	1973	Poor adhesion
Yankton	Polyurethane elastomer	Goodyear	1974	Poor adhesion
Sauk	Polyphenylene oxide	RPI	1973	Poor adhesion
Sauk	Polyurethane rigid	Dexter	1973	Good
Sauk	Bituminous epoxy	International Red Hand Paint Co.	1974	Pending
Raritan	Polyurethane nonsolvented	Xenex	1974	Very good
Mackinaw	Polyurethane port side elastomer stbd. side rigid	Hughson	1974	Poor
		Hughson		Fair
Mackinaw	Polyurethane nonsolvented	Xenex	1975	Pending
North Wind	Polyurethane rigid	Hughson	1975	Pending
West Wind	Glass flake polyester	Baltimore Copper Paint	1974	Fair

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10.1 USCG Cutter Yankton

The overall dimensions of the Cutter Yankton are:

100 ft long

27.3 ft beam

12.25 ft draft

384 tons maximum displacement steel hull.

As described in the Phase I, Part II progress report (Ref.2), bonding problems were found between the coating and the undercoat during the 73-74 icebreaking season.

The following comments pertain to the coating which remained on the hull after the 73-74 icebreaking season.

Some of the polyurethane remained intact on the hull after the icebreaking season. It contained barnacles and other marine growth.

This material could be easily washed off of the surface with water from a high pressure hose. The barnacles did not penetrate the coating and none were attached so strongly that they could not be removed by pressure applied by hose. The coating surface beneath the barnicle was not damaged in any way. Most of the epoxy primer was still intact on the ship. The separation in the coating appeared to be between the polyurethane elastomer and the epoxy primer. Very little epoxy primer was seen on the back of the polyurethane coating indicating little or no chemical bond between the primer and the top coat.

10.1.1 Recoating of the Yankton

The ship was recoated with the Goodyear system top coat but the undercoat was changed on the port side from midship to stern and in a small area near the bow. The primer used on the rest of the ship was polyamide epoxy containing aliphatic amines manufactured by Devoe and Reynolds. The new

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primer on the port side was a wash primer manufactured by Hughson.

The coating which remained intact was extremely abrasion resistant to the point that a grit blast surface preparation would not easily remove it. The loose material was removed and the surface was reactivated (MEK wash) to accept a new topcoat of polyurethane. This procedure for reactivating the coating to obtain a chemical bond to subsequent layers was recommended by the coating manufacturer. In addition, if precipitation occurred between coating layers (overnight), the MEK reactivation procedure was again used. The coating was applied with a Greyco airless spray gun and a 'pot' reservoir. The weather conditions during the coating period are shown in Table II-1. It can be seen from this table that the weather conditions were still poor for coating application. Due to scheduling, the ship had to be coated and put back in the water during high tide or it would require an extra 30 days before launching.

The properties of the coating taken during the application period are seen in Table II-2 and Table II-3. Photographs of the USCG Cutter Yankton during the coating application are seen in Figures II-1 through II-3.

The ship was examined after it was put back into the water to determine the condition of the coating after exposure to water but before icebreaking service.

The Yankton saw service on the Atlantic Coast, near Portland, Maine during the 74-75 icebreaking season.

The coating performance was again poor. The coating was removed at the water line very similar to the past year's performance. The primer remained intact while the polyurethane elastomer separated at the interface between the topcoat and primer. The bulk of the urethane removed was at the water line but some of the material came off beneath the water line. The urethane

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on the wash primer did not show any significant improvement over that on the polyamide epoxy primer. Photographs of the Cutter Yankton are seen while setting in the water after 1974 to 1975 icebreaking season, Figure II-4.

The results of these tests indicate that this material was not useable in its present state of development for icebreakers since the bond between the urethane and primer does not appear adequate.

It is not known if the problem exists as a result of poor application conditions, or deterioration after exposure to environment. However, the environmental conditions cannot be easily changed.

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TABLE II-1

WEATHER CONDITIONS DURING THE RECOATING OF THE USCG CUTTER YANKTON

- May 15, 1974 - Grit blasted the port side. Could not remove all of the coating from the port side. Grit blasted the bare metal from midship to stern. Applied wash primer to the port side midship to stern. Rained on and off all day. Temperature - 65°F, (18°C), Humidity - 75%
- May 16, 1974 - Could not grit blast the rest of the urethane coated hull. Unable to get through the urethane. Tried scorching the area with a torch. Decided to reactivate the existing primer and urethane and apply material to the top.
- May 21, 1974 - Applied 1 mil of new primer to the starboard where the old primer was intact. Applied 3 mils to all base metal on starboard and port side. Temperature - 60°F, (16°C), Humidity - 70%.
- May 22, 1974 - Cleaned existing urethane with MEK. Applied two coats of fresh polyurethane to the port side. Started to rain at 2 p.m. Rained for 45 minutes. Started to coat at 4:30 p.m., continued until 9:00 p.m. Temperature varied between 60 - 70°F (16-21°C) Humidity - 70 to 80%. Applied third coat to the port side.
- May 23, 1974 - Very heavy rain during the night. Cleaned all surfaces with MEK. Applied two full coatings to the entire ship. Temperature - 60°F, Humidity - 60%. Final topcoat applied during afternoon.

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TABLE II-2

TABULATION OF THE COATING PROPERTIES OBTAINED DURING THE
APPLICATION TO THE HULL OF THE USCG CUTTER YANKTON

	Polyurethane and Polyamide Primer	Polyurethane and Wash Primer
Minimum average bond strength of primer	550 psi	850 psi
Minimum average bond strength of polyurethane	800 psi	1017 psi
Tensile strength of coating	2000 psi	2000 psi
Final surface roughness	70 to 120	70 to 120
Coating thickness primer	3 to 4 dry mils	5 dry mils
Coating thickness	20 to 22 dry mils	16 to 20 dry mils
Hardness (pencil)*	E4 to E5	E4 to E5

* Coating deformed under pencil test but did not damage. Deformed area recuperated after a short period of time.

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TABLE II-3

BOND STRENGTH MEASUREMENTS TAKEN DURING THE SECOND COATING
OF THE USCG CUTTER YANKTON

Specimen	Bond Strength	Remarks
Wash primer only	950 psi	Broke between the primer and the steel
Wash primer only	750 psi	Broke between the primer and the steel
Wash primer + polyurethane	1122 psi	Broke at the primer
Wash primer + polyurethane	904 psi	Broke at the primer
Polyamide Primer	680 psi	Broke in primer
Polyamide primer	420 psi	Broke in fixture epoxy
Polyamide primer + polyurethane	625 psi	Broke in polyurethane undercoat
Polyamide primer + polyurethane	975 psi	Broke in polyurethane undercoat

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Figure II-1a Condition of the Hull of the US Cutter Yankton before Recoating



Figure II-1b Condition of the Hull of the US Cutter Yankton after Reactivation of the Primer but before Polyurethane Coating

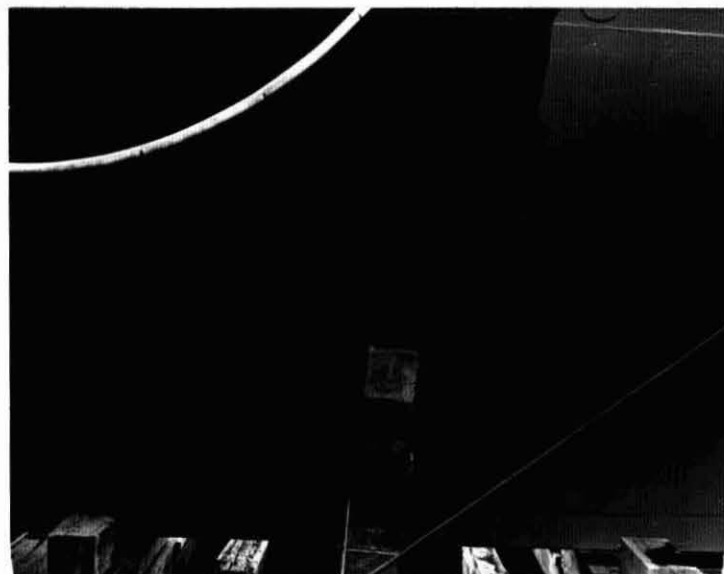


Figure II-2 Condition of the Hull of the Yankton Showing the Type of Primer Used



One Coat of Urethane



Three Coats of Urethane



After Final Coat of Urethane

Figure II-3 Condition of the Hull of the US Cutter Yankton during Various Stages of Urethane Coating



Figure II-4 Photographs of the US Cutter Yankton after Icebreaking Service

10.2 USCG Cutter Sauk

The overall dimensions of the Cutter Sauk are:

- 110 ft long
- 27.3 ft beam
- 12.25 ft draft
- 384 tons maximum displacement - steel hull.

The coating applied to the hull in November 1973, was the Dexter Polyurethane Laminar X 500. This is essentially a two-part chemical cure polyurethane applied over a zinc rich polyamide epoxy primer.

The coating was applied over a "near white" grit blast surface preparation. The primer and polyurethane were applied by a conventional air type spray gun with a "pot" supply system. The weather conditions during the coating application are seen in Table II-4.

The surface roughness measured was as follows:

- (a) Sand blasted hull - greater than 400 μ " CLA.
- (b) Primed hull - 300 μ " to greater than 400 μ " CLA.
- (c) After three coats of polyurethane - 60 μ " CLA.

It should be noted that these values are the average roughness of the hull plates, but not of the welded areas or of the areas where severe pitting had occurred. Some of the shallow pits are filled in with the coating system but on the keel and in areas where the hull plates are older or damaged, the pits are as much as 100 mils deep. The coating is not sufficient to fill these pits.

Overall photographs of the hull after grit blasting and priming are seen in Figures II-5 and II-6.

Test specimens for bond strength measurements were taken periodically during the coating period. These specimens were left out overnight to cure under the same conditions as the ship coating. The bond strength was measured in tension. The results are given in Table II-5.

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TABLE II-4

WEATHER CONDITIONS
USS SAUK

- November 19 - Weather was partly cloudy. Temperature 10°C (50°F). Relative humidity 50%. Approximately 90% of the starboard side was grit blasted and allowed to stand overnight.
- November 20 - Weather was clear. Temperature 10°C (50°F). Relative humidity - 50%. The rest of the starboard side and the port side were grit blasted. The urethane primer was applied to the starboard side. The coating thickness was .6 to 1.0 dry mils. The coating was very thin to the point where the hull appeared to be dusted as shown in Figure II-5. This is a recommended applying procedure for this primer which utilizes both a chemical bond and a mechanical bond to the substrate. The zinc rich polyamide epoxy primer was applied on the port side from midship to stern. The coating was allowed to set for three hours and the first coat of polyurethane was applied. The first coat was allowed to set overnight. The temperature dropped to below -1.0°C (31°F).
- November 21 - The polyurethane felt dry to the touch. Total thickness was 3.0 to 4.0 dry mils. Weather was clear and sunny. Temperature -1.0°C (31°F). Relative humidity 60%. Started to apply second coat at 7:45 a.m. The total thickness after the second coat was 4.0 to 5.0 dry mils. Started to apply the final coat at 10:30 a.m. Temperature was 5.6°C (42°F). Relative humidity 65%. The total thickness was 6.5 to 8.5 dry mils. After the last coat was applied, the ship was allowed to set in dry dock for four days before it was put back into the water.

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Figure II-5 Hull Appearance of the USCG Cutter Sauk after Grit Blasting

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Figure II-6 Appearance of the Hull of the USCG Cutter Sauk
after Grit Blasting and Priming

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TABLE II-5

ADHESION BOND STRENGTH OF POLYURETHANE TO THE USCG CUTTER SAUK

Date Taken	Specimen Number	Bond Tensile Stress (psi)	Remarks
November 20	Undercoat only	425	Cohesive failure
November 20	1	471	Broke in the epoxy
November 21	2	565	Broke in the epoxy
November 21	3	525	Broke in the epoxy

The undercoat is the only cohesive failure that was seen in these tests. The values obtained on the polyurethane all broke in the fixturing epoxy and are a minimum value of the coating system. It became evident that any failure seen should appear in the undercoat.

Photographs of the keel section of the USCG Cutter Sauk at the bow, are shown in Figure II-7. This photograph shows the extreme difference in surface roughness on the plates, weld and keel. The surface roughness of the plate is between 30 and 60 μ ".

The ship was put back into the water for service on the Hudson River throughout the icebreaking season. On March 5, the hull was examined for damage while the ship was in the water. Therefore, the following observations pertain to the areas near or just below the water line.

During the season the ship had logged 40.25 hours of icebreaking. It had broken both hard ice and the "pack ice" which is the small granules of ice particles compacted together. According to the information obtained on the ship, the hard solid ice appeared to present little problem with the coating.

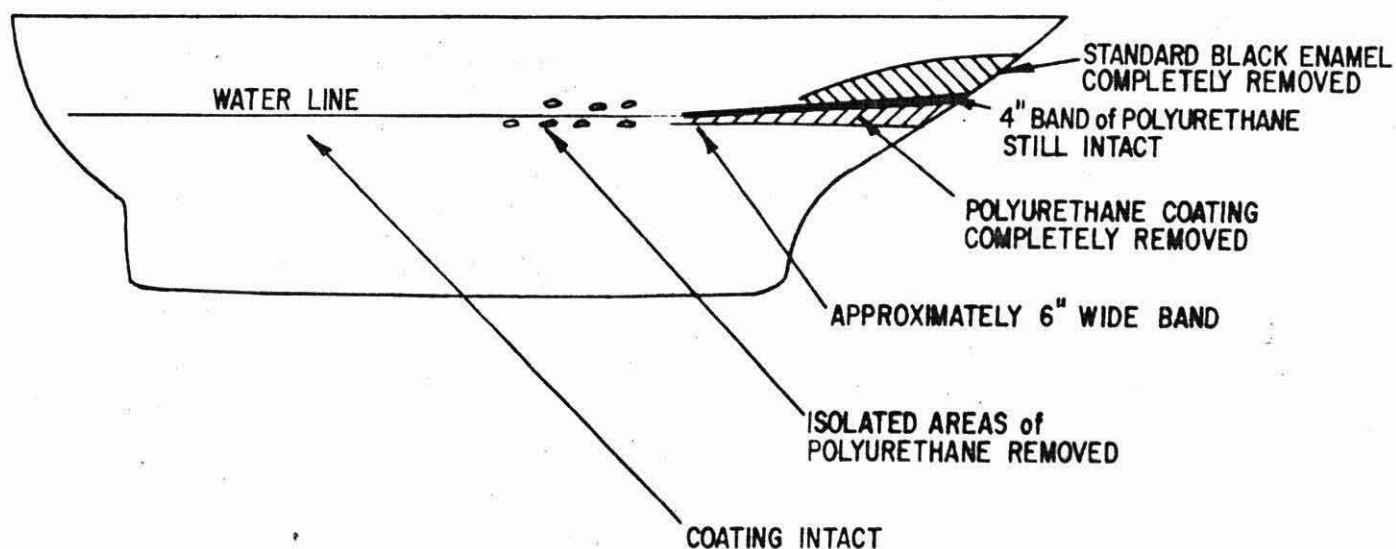
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Figure II-7 Photograph Showing the Difference in Surface Roughness of Plate, Weld and Keel Sections of the Bow of the Cutter Sauk

The conventional black enamel paint at the bow above the water line was completely removed from the hull. Just below that, a strip approximately four inches wide of polyurethane was still intact on the bow. This substantiated the information obtained in that the conventional enamel could only have been removed by heavy ice at the bow but it did not remove the polyurethane.

After the ship had been in the "pack ice" it was noticed that a band of polyurethane at the water line and below it was being removed. This is attributed to the erosion or abrasive action of the small particles of ice impinging on the hull. The total width of the urethane being removed at the bow was not visible; however, the width could be seen approximately ten feet from the bow and estimated to be about six inches. About 20 feet back the coating was intact at approximately 90% of the water line. From midship to stern, the coating appeared to be 100% intact at the water line. The diagram below shows the approximate extent and pattern of the damage.



The ship was put into dry dock during the month of October and a more detailed examination of the hull was made.

Approximately 90% of the coating was still intact. The only wear problem was seen at the water line. The coating above and below the water line showed no signs of abrasion. The material still remaining on the ship was attacked by fouling, barnacles and a coating of residue or slime. This residue could be wiped off the coating leaving the bright original finish which was seen during the coating application. Photographs of the typical appearance of the hull are seen in Figure II-8.

The barnacles attached to the coating could be easily removed by simply pushing against them with a finger leaving the coating underneath undamaged. The barnacles did not penetrate the coating surface. It is unusual to be able to remove barnacles with such little effort. Normally the means to remove them is to grit blast or scrape them from the surface. They are usually so firmly attached to the surface that removal means damage to the coating.

One portion of the coating was removed and returned to RPI for close examination. Photomicrographs of the surface are seen in Figures II-9 and II-10. Figure II-9a shows the typical surface appearance as seen coming out of the water. Figure II-9b shows the same area with the larger barnacles removed. The white material in the center is the adhesive which the barnicle uses to attach itself to the coating. This material can be easily removed with water. Figure II-10a shows a portion of the coating as it appears on the ship (left) and a portion of the coating which was cleaned with water. Note all of the material was easily removed except for the slight discoloration where the growth had been. It should be stressed that the only fluid used for removal was water. Figure II-10b shows the same area with the large barnicle removed. Table II-6 shows a comparison of the coating properties before and after service.

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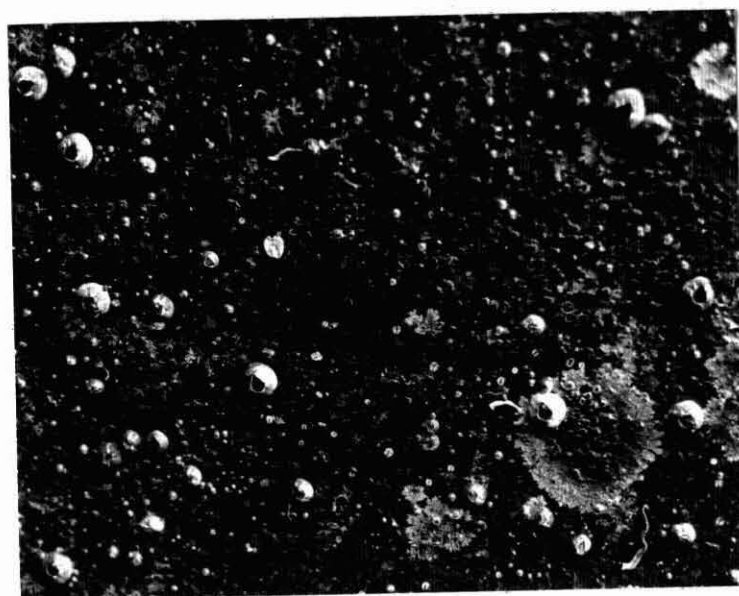
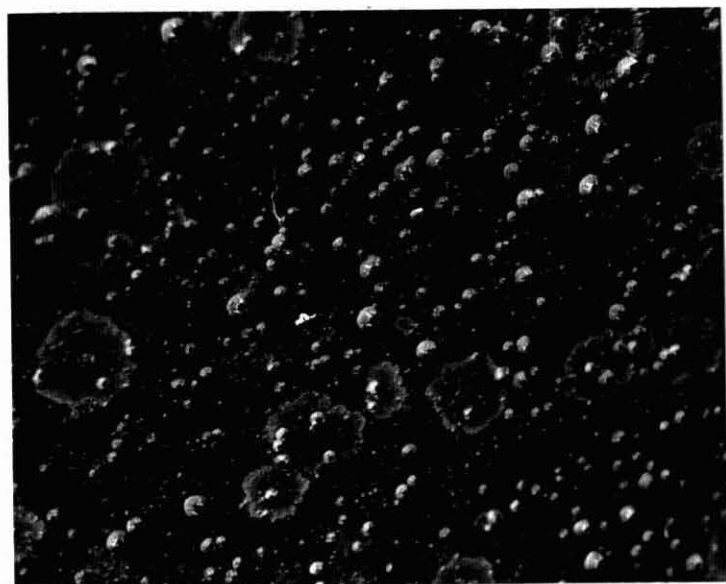
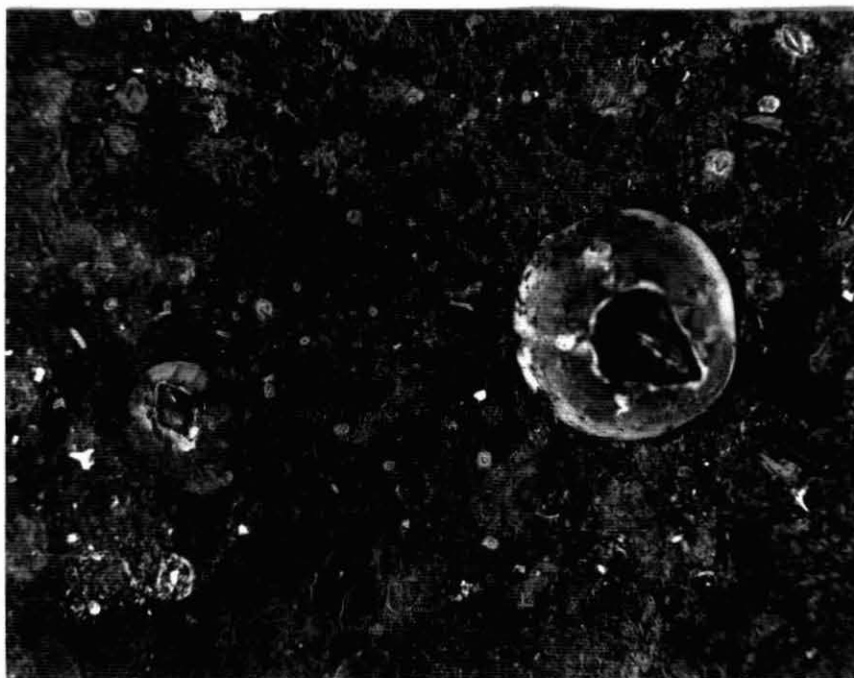
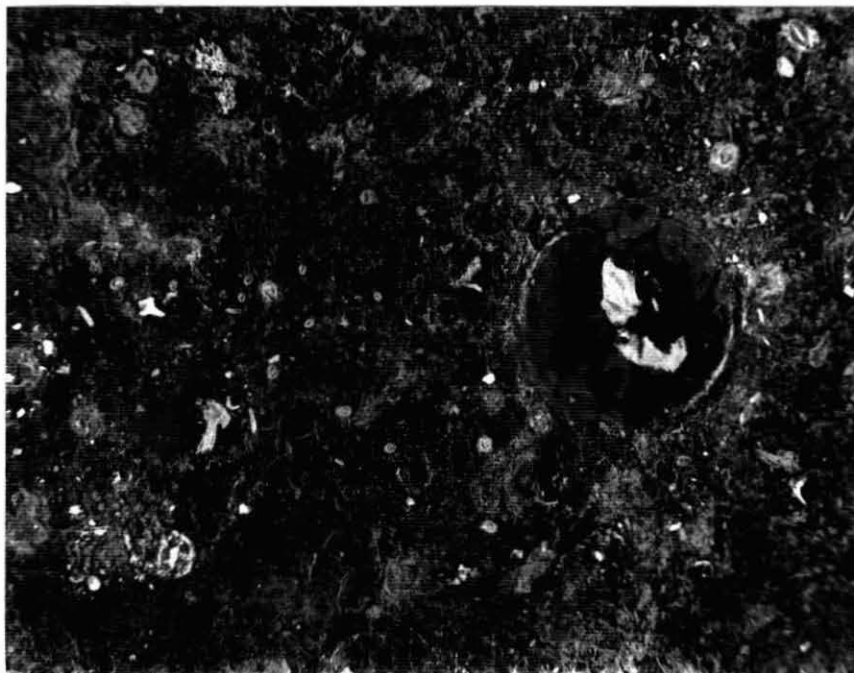


Figure II-8 Hull Surface of the USCG Cutter Sauk after One Year of Icebreaking Service.



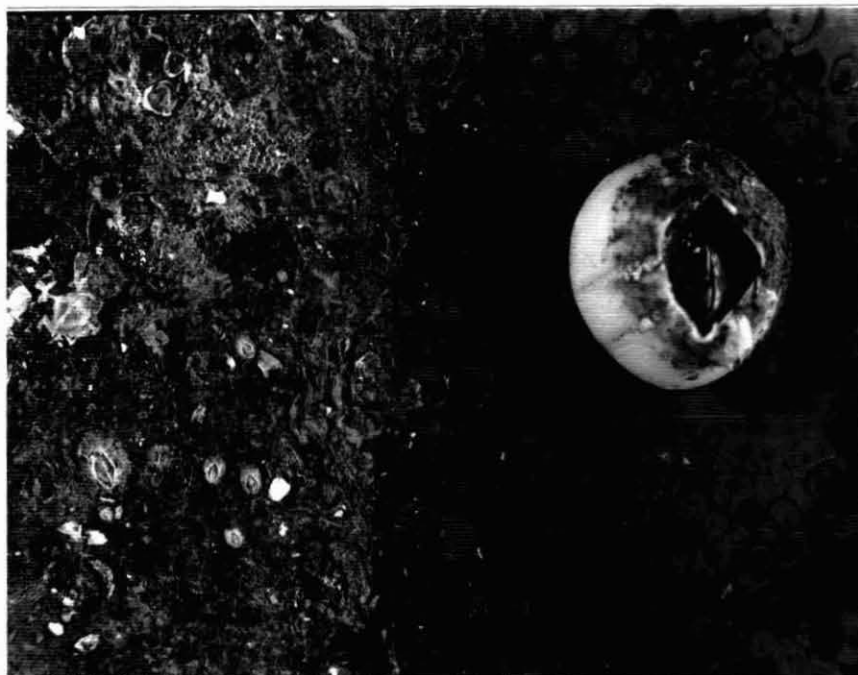
a.



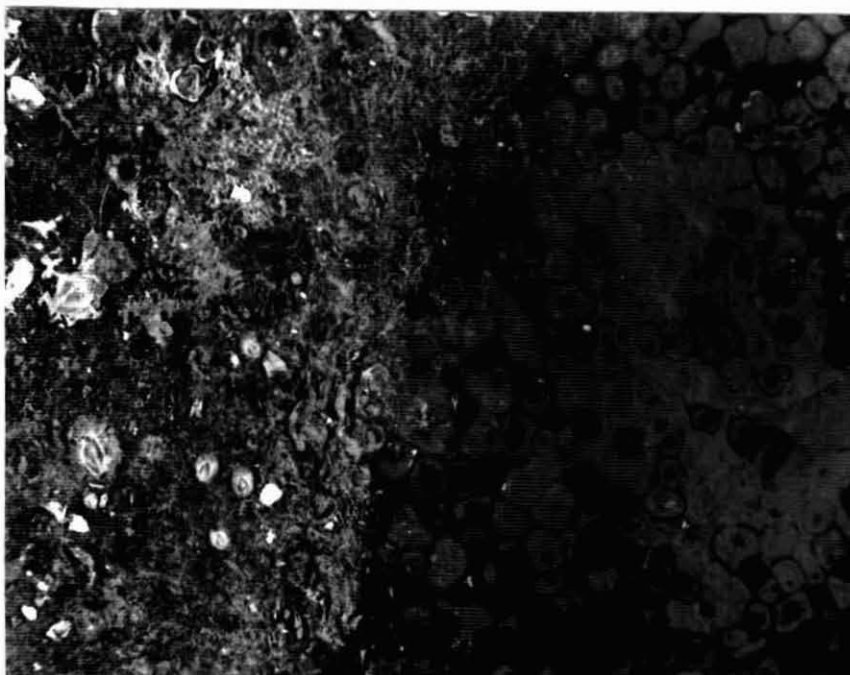
b.

Figure II-9 Surface Appearance of the Coating on the Hull of the USCG Cutter Sauk after Service. Upper photo shows the typical appearance of the coating as "dry docked". Lower photo shows the barnacles removed without damage to the coating magnification $\times 3$.

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a.



b.

Figure II-10 Surface Condition of the USCG Cutter Sauk Coating before (Left) and after (Right) Washing with Water. Upper photo shows position of a barnacle on the cleaned surface. Lower photo shows the barnacle removed. Magnification 3X.

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TABLE II-6

COMPARISON OF THE DEXTER POLYURETHANE COATING
BEFORE AND AFTER ICEBREAKING SERVICE
USCG CUTTER SAUK

	Before Service	After Service
Average thickness	6.5 to 8.5 mils	6.5 to 7.5 mils
Average surface roughness	60 to 100 μ "	Before cleaning > 400 μ " After cleaning 100 to 150 μ "
Hardness (pencil)	Would not scratch	Would not scratch
Coating appearance	Brilliant red	Slightly discolored. Some darker areas where growth had been removed.

Essentially very little significant change in the coating was noted below the water line. The surface roughness before service was 60 to 100 μ " and the surface after service and after cleaning was 100 to 150 μ ". The ability to remove the bulk of the barnacles and fouling material without change to the coating is a definite advantage since this could mean that the ship's hull could be cleaned without the need for grit blasting.

Coating hardness did not appear to change before and after service. The coating could not be scratched with the hardest lead.

The thickness was measured over 50 points on the hull and found to have changed a maximum of .001". The maximum reading taken before service was .0085" and the maximum reading taken after service was .0075".

10.2.1 Recoat of the Cutter Sauk

The Cutter Sauk was recoated with a conventional bituminous coating during October 1974. At that time coating bond specimen, surface roughness measurements and hardness readings were taken during the coating application.

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The coating applied was a

Red lead primer - 2 to 4 dry mils

Coal tar epoxy - 6 to 8 dry mils per coat, 2 coats

Vinyl red antifoul - .5 to 1.0 dry mils per coat, 2 coats.

The bond strength values obtained on the hull coating are seen in Table II-7.

The vinyl antifoul is the weakest link in the system and is of course not expected to remain on during the icebreaking season. However, that coating is only meant to retard marine growth during the warmer months.

TABLE II-7

ADHESIVE BOND STRENGTH OF BITUMINUS COATING ON THE USCG CUTTER SAUK

Date Taken	Specimen No.	Bond Thermal Stress (psi)	Remarks
October 22	Undercoat only	635	Broke in the epoxy
October 22	Undercoat only	785	Broke in the epoxy
October 22	Undercoat only	635	Cohesive failure
October 23	Bituminus	790	Cohesive failure
October 23	Bituminus	835	Broke in the epoxy
October 23	Bituminus	910	Broke in the epoxy
October 24	Vinyl antifoul	120	Cohesive failure
October 25	Vinyl antifoul	102	Cohesive failure
October 26	Vinyl antifoul	210	Cohesive failure

The surface roughness of the hull was as follows:

after grit blast - $> 400 \mu''$

after primer - $> 400 \mu''$

after coal tar epoxy - 250 to $> 400 \mu''$

after 2 coats vinyl - 190 to $350 \mu''$.

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There is little reduction in roughness of the hull as a result of coating. This is due to the particles of antifouling material (PbO, CuO, etc.) contained in the vinyl topcoat. In Figure II-11, a glaze is seen on the coal tar epoxy but after the vinyl antifoul was applied, a dull finish resulted. Therefore the final coat does not decrease the roughness but in some cases can increase the roughness of the hull.

Photographs of the USCG Cutter Sauk during the coating are seen in Figure II-11.

10.3 USCG Cutter Mackinaw

290 ft long

74 ft beam

19 ft draft

5252 tons displacement - steel hull.

The bow of the Cutter Mackinaw was coated in 1974 with the Hughson polyurethane system. The original intention was to coat the entire hull but because of weather conditions, labor problems and labor strikes, approximately one third of the ship was coated. The coating was applied to both sides of the bow and progressed back to midship.

The coating system used was as follows:

Starboard	Port
9924 Wash Primer	9924 Wash Primer
Chemglaze II	Elastomer
	Chemglaze II

Table II-8 shows the results of the bond strength measurements and other data obtained during the coating application.

Photographs of the Cutter Mackinaw during the coating are seen in Figure II-12.

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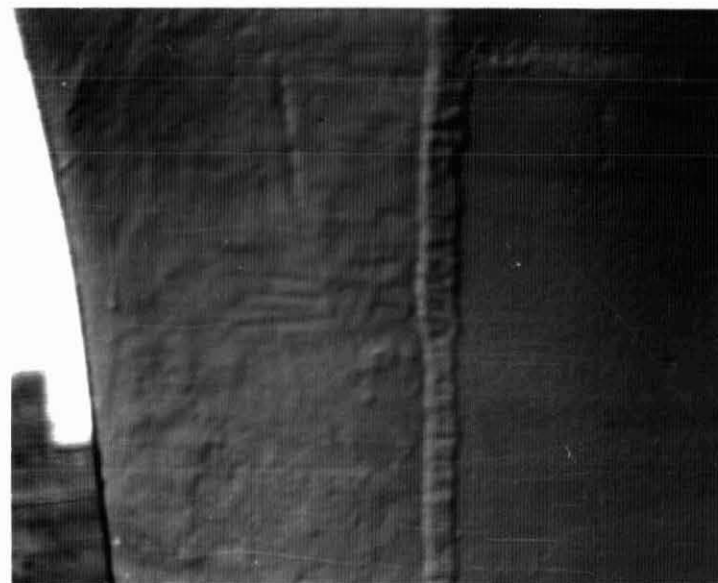
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Overall View of the Cutter Sauk after Coating the Hull



After coal tar epoxy high build coat



After Vinyl antifoul

Figure II-11 Hull of the USCG Cutter Sauk after Application of a Conventional Epoxy System and a Vinyl Antifoul

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TABLE II-8

TABULATION OF THE PROPERTIES OF THE HUGHSON CHEMICAL
POLYURETHANE APPLIED TO THE HULL OF THE
USCG CUTTER MACKINAW

	Starboard	Port (Elastomer)
Minimum average bond strength of the primer	-	-
Minimum average bond strength of the polyurethane	865	455
Final surface roughness	> 400 μ'' CLA*	> 400 μ'' CLA*
Coating thickness average (below boot top)	3.5 to 5 dry mils	8.0 to 12.0 dry mils
Coating thickness average (boot top)	7 to 8 dry mils	18 to 20 dry mils
Coating thickness average (primer)	.4 to .7 dry mils	.4 to .7 dry mils
Hardness (pencil)	E2 to E3	Could not scratch

* Unable to obtain accurate surface roughness measurements due to the large and numerous pits in the plating.

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Figure II-12 Photographs of the USCG Cutter Mackinaw during and after Application of Polyurethane Coating. Port side elastomeric system, starboard side rigid urethane system

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Successive grey and black coats were applied to build up to the final thickness. This is to insure full coverage with each coat. The thickness of each coat was measured with a wet film measurement gage during the application and after curing with a dry film magnetic gage.

The primer was applied over a "white metal" grit blasted surface preparation. The grit used was SiO_2 . Coating application was accomplished with a conventional air spray gun and a "pot" source.

During the application, test samples of the coating were taken as well as surface roughness measurements, thickness and hardness measurements. The results of the evaluation and strength measurements are tabulated in Table II-9. The hull surface contains many pits. In some cases these pits were .250" deep, making it very difficult to obtain roughness measurements after coating. Some typical surface pits are seen in various photographs in Figures II-13 and 14. The urethane coating was not sufficient to fill in these pits leaving the surface very rough after coating.

TABLE II-9

BOND STRENGTH VALUES OBTAINED DURING THE COATING OF THE USCG CUTTER MACKINAW

Specimen	Bond Strength (psi)	Remarks
Primer only	585	Broke in the epoxy
Primer only	650	Broke in the epoxy
Elastomer + primer	487	Broke in the elastomer
Elastomer + primer	410	Broke in the elastomer
Elastomer + primer + Chemglaze II	468	Broke between the elastomer + primer
Primer + Chemglaze II	988	Broke in the epoxy
Primer + Chemglaze II	800	Broke in the epoxy
Primer + Chemglaze II	907	Broke in the epoxy

Coating conditions during application are shown in Table II-10.

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Figure II-13 , Typical Surface of the Hull of the Cutter Mackinaw
after Grit Blasting

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Figure II-14 Surface of Hull of Cutter Mackinaw after Application of the Elastomeric System to the Port Side. Note very heavy pitting on the hull plating.

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TABLE II-10

CONDITION FOR APPLYING THE COATING TO THE HULL OF THE USCG CUTTER MACKINAW

- May 29 - Sandblasted and primed tests area 200 sq ft. and applied wash primer. Temperature 16°C (60°F), humidity 40%. Coating thickness between .2 and .5 dry mils.
- May 30 - Sandblasted bow near the water line. Temperature 13°C (56°F), 64% humidity. Very light rain for about 10 minutes during the morning. Applied primer to the boot-topping near the bow at 4:15 p.m. Temperature 16°C (60°F), humidity 65%. Finished priming at 5:00 p.m. Temperature 13°C (56°F), humidity 70%. Rained during the night.
- May 31 - Sandblasted bow section below the boot-topping. Temperature 6°C (42°F), humidity 70%.
- June 1 - Temperature 20°C (68°F), humidity 38%, continued to sandblast and prime port side approximately 30 ft from the bow
- June 3 - Reblasted and primed area done on June 1. Appears to be poor coverage. Temperature 17°C (63°F), humidity 65%.
- June 4 - Grit blasted and primed area on the port side. Temperature 23°C (73°F), humidity 54%.
- June 5 - Grit blasted and primed more port sides. Temperature 21°C (70°F), humidity 63%.
- June 6 - Grit blasted port side. Temperature 18°C (64°F), humidity 84%.
- June 7,8,9,10 - Did not work. Unstable weather conditions. Rained on and off throughout this period.
- June 11 - Grit blasted and primed starboard and port areas approximately 80 ft back from the bow. Temperature 17°C (63°F), humidity 58%.
- June 12 - Grit blasted and primed port side in area below the boot-topping and starboard sides near keel. Temperature 18°C (66°F), humidity 44%.
- June 13 - Grit blasted and primed starboard side areas near the keel approximately 60 ft back from the bow. Temperature 17°C (63°F), humidity 64%.
- June 15-17 - Did not work. Heavy rain throughout this period.
- June 18 - Cleaned primed hull and touched up area where primer is thin. Started to apply Chemglaze II to starboard side. Temperature 62°F (17°C), humidity 60%, hull temperature 16°C (61°F). Thickness measurements 1.4 to 1.8 dry mils.

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Table II-10 - cont'd.

- June 19 - Applied second coat of Chemglaze II to the starboard side and first coat of elastomeric to the port side. Temperature 14°C (62°F), humidity 65%, hull temperature 16°C (61°F). Portion near the keel at the bow was wet due to condensation of moisture from water on the deck floor. Cleaned area with solvent and dried with air blast. Wiped area with paint thinner and applied first coat of Chemglaze II.
- June 20 - Applied second coat of elastomeric to the port side. Applied third coat of Chemglaze II to the starboard side. Temperature 17°C (63°F), humidity 57.5%, hull temperature 64°F (18°C). Afternoon - continued spraying elastomeric and Chemglaze II.
- June 21 - Finished final coat of Chemglaze II on the entire ship. Temperature 16°C (61°F), humidity 82.5%, hull temperature 18°C (64°F).

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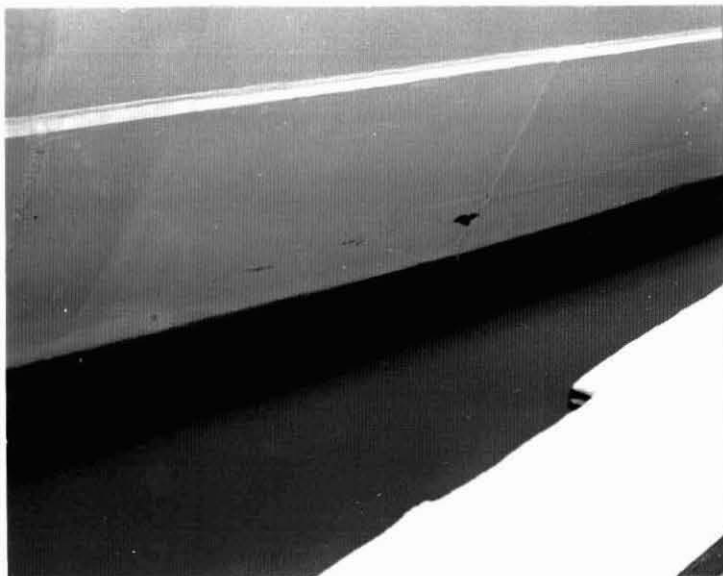


Figure II-15 Photographs of the Ice Line of the Hull of the Cutter Mackinaw after Icebreaking Service

10.3.1 Results of the Evaluation

During the winter, the ship logged over 600 hrs of icebreaking. The hull was examined while still in the water (Figure II-15) by divers during the month of April and again when dry docked during June. The results are as follows.

Port Side (Elastomer) - The coating was completely removed from the top of the boot-topping down to about the 15 ft line. Below that, the elastomer was still intact but heavy rust was coming through the coating. It appeared as though the elastomer was extremely porous, allowing water into the substrate and leaching rust on the surface. Most of the topcoat of Chemglaze was removed from the elastomer and some of the grey layer beneath the black top was visible. Coating thickness was .008" to .012" where the coating was intact.

In areas where the coating was removed (boot-topping) no primer was evident.

The coating was scratched with lead between E4 and E3. The original hardness measurements showed that the coating could not be scratched due to its elasticity. This indicates that the increase in hardness could be a result of continued curing or aging after exposure to one year of water.

Essentially the elastomeric coating showed very poor results with gross material removal and even where the material was not removed, a significant amount of rust was penetrating the coating to the surface.

Starboard Side (Chemglaze II) - The starboard side had material removed from the water line to six feet below the water. No primer could be seen in this area. The primer could be seen approximately three feet below that. Essentially, the Chemglaze was removed from the water line to nine feet below the water. The Chemglaze was intact from the nine foot mark down to the keel. The only areas where rust could be seen were at the tips of the surface roughness asperities. This represented less than 1% of the total surface where the coating was intact. The coating thickness below the nine foot mark was .005 to .007". The coating

would not scratch with any lead indicating that it had hardened during the year of service. After application, the hardness was E2 to E3. The increase in hardness (similar to the elastomer) can be attributed to continued curing during the year or aging of the polyurethane.

10.4 Full-Scale Test Observations

At this point of the evaluation the following comments should be made concerning the coatings:

- (A) Elastomer on the Cutter Yankton - Moisture cure polyurethane - poor results. Heavy wear bonding problems.
- (B) Elastomer on the Cutter Mackinaw - Chemical cure polyurethane - poor results. Heavy wear.
- (C) Rigid urethane on the Cutter Sauk - Chemical cure polyurethane - fair to good results. Wear only at the ice line.
- (D) Rigid urethane on the Cutter Mackinaw - Moisture cure polyurethane - fair results. Wear mainly at the ice line.

It becomes evident that the standard elastomeric urethanes do not have the bond strength or tenacity to remain on the surface during icebreaking service, regardless of the type of cure system (chemical or moisture cure).

The rigid polyurethanes appear to have more resistance to damage during icebreaking service on all areas except at the ice line itself where the maximum forces are seen. This is again regardless of the curing system:

10.5 Recoat of the Cutter Mackinaw

During June 1975, the bow of the Cutter Mackinaw was recoated with a non-solvent polyurethane system. The nonsolvent material had been applied to the Cutter Raritan and gave very promising results during the 74-75 icebreaking

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season. (The Cutter Raritan tests will be discussed later in this section.)

The coating was applied to the bow and on a 10 ft strip from the top of the boot-topping down. One quarter inch of material was applied to the bow, port side and 1/10 inch was applied to the starboard bow section. Since this material was successful on a small ship (110 ft icebreaking tug) the need to test it on a larger vessel became apparent and the adequate applied thickness could not be determined except through full-scale tests.

Further back on the sides of the ship the coating was tapered to approximately .030". The taper started approximately 30 ft from the bow stem and progressed over a 4 to 6 ft section to .030".

An attempt was made to fill in the hull pits with the coating material. This was accomplished as follows:

1. Grit blast to a "commercial blast" surface preparation.
2. Clean all surfaces with Toluene.
Apply a thin film of primer (.005 to .001").
3. Apply nonsolvented polyurethane and squeegee the excess coating leaving a very thin film on the surface while most of the coating remained in the pits.
4. After curing, lightly grind any high points of coating to form a uniform surface.
5. Clean all surfaces with Toluene. Apply the next coat of material and build to the desired thickness.
6. Touch up any areas with a hand mix material to further reduce the surface roughness.

The coating can be applied to any thickness up to one inch. Therefore only one spray time is needed to build up the coating.

Photographs of the coating and squeegeeing process are seen in Figures II-16. Note one man applying the coating with a spray gun while two others follow him

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Figure II-16 Photographs Showing the Application of the First Coat of Nonsolvented Polyurethane. This coating was applied and then squeegeed down to fill the pits on the hull of the ship. Subsequent coatings were applied to build up the coating and obtain coverage.

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with rubber squeegees to remove the surface coating leaving the voids filled with material.

Figures II-17, 18 show photographs of the coating after the final coat was applied. Some of the photographs (Figure II-17) were taken near the coating edge to compare the bare metal and pits next to the coating. Overall views of the hull are seen in Figure II-18 after coating. These photos show the final surface texture obtained which is not completely smooth but certainly much smoother than the original pitted surface and much smoother than would be obtained by simply applying a coating to the hull as compared to Figure II-14. The discolored areas seen on the bow are a result of the touch-up material used to further reduce the surface roughness as the last step in the procedure. This material is essentially the same as the sprayed coating except it is applied by hand mixing and trowelling on the surface.

It should be noted that a series of tests were run during the Part I portion of this report to apply a filled primer to the hull for the purpose of reducing the hull roughness. This was not done in this instance because the coating used (nonsolvented polyurethane) is normally a high viscosity material and did not require any filler in order to fill the hull pits. The material can be applied in heavy layers without the problem of dripping or running.

The coating conditions during application are shown in Table II-11.

The coating properties are shown in Tables II-12 and II-13.

The ship was put back into the water to see icebreaking service during the 75-76 icebreaking season.

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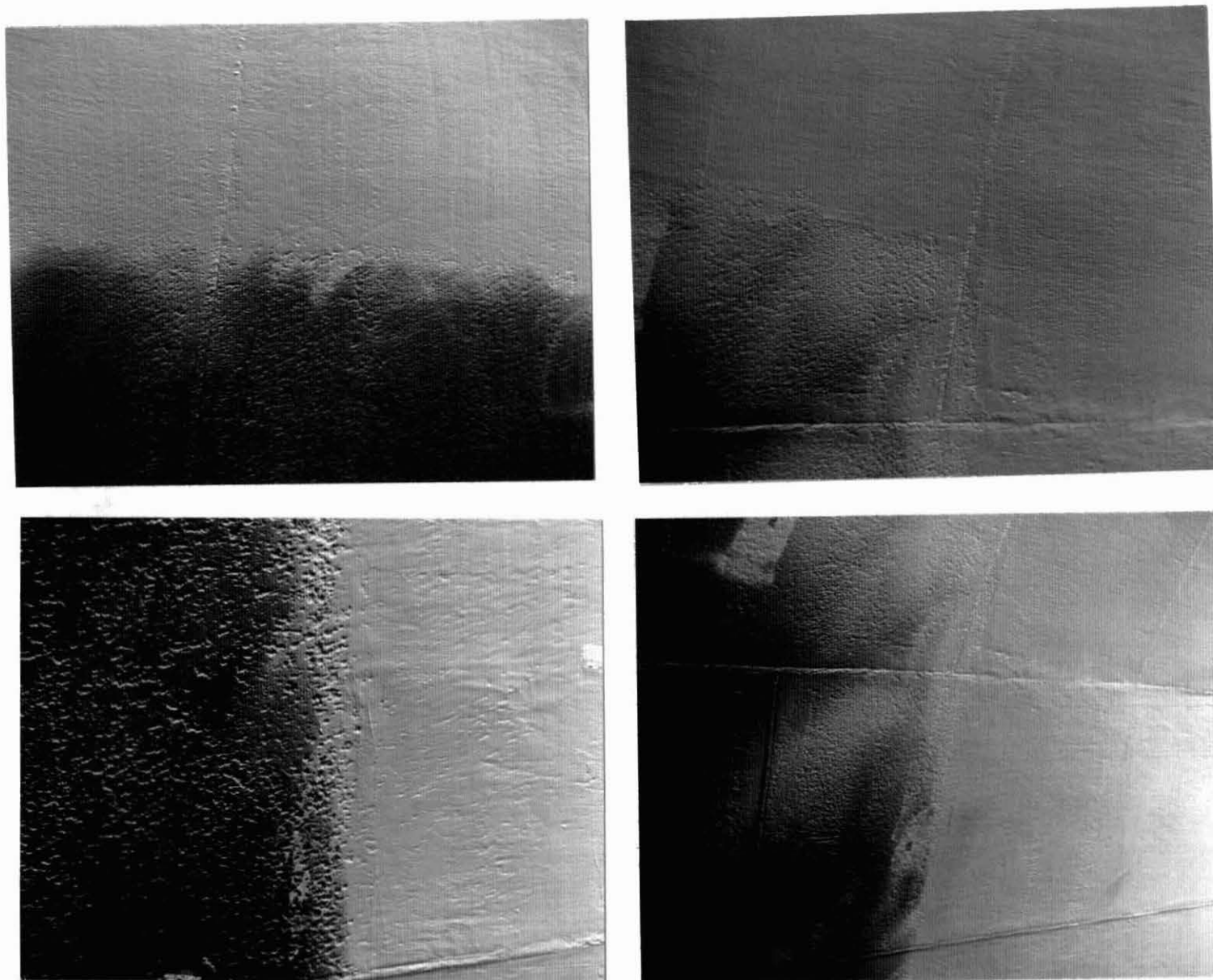


Figure II-17 Typical Hull Appearance of the USCG Cutter Mackinaw after Coating with Nonsolvented Urethane. Note the base metal showing the pits in the metal before application.

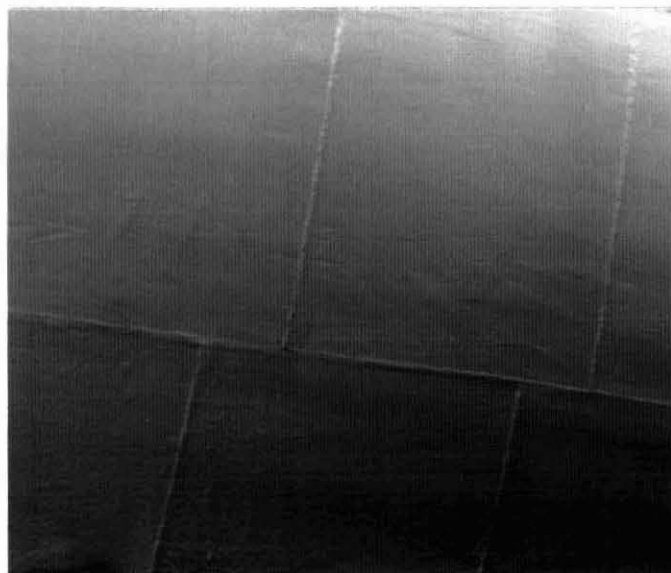
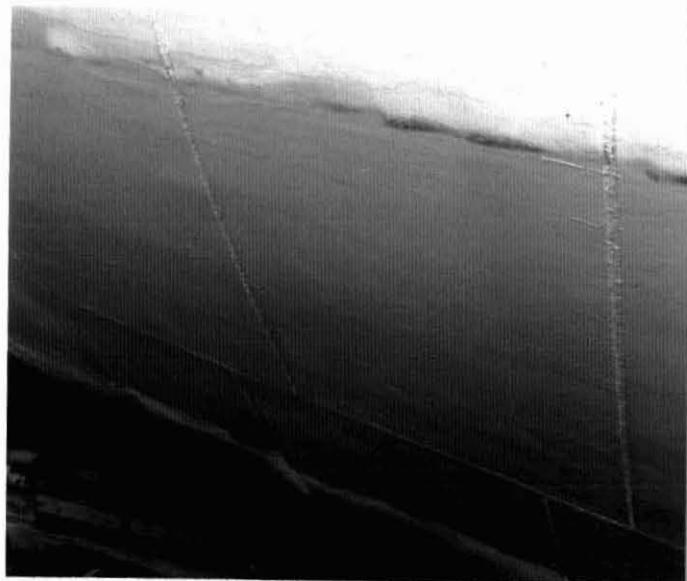


Figure II-18 Overall View of the Hull of the USCG Cutter Mackinaw after Applying the Nonsolvented Urethane

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TABLE II-11

APPLICATION CONDITIONS DURING THE COATING OF THE BOW OF THE USCG CUTTER MACKINAW

- June 2, 75 - Grit blasted starboard side.
- June 3, 75 - Rained most of the day, grit blasted port side. Had to use paint stripper on the port side to loosen the remaining elastomer.
- June 4, 75 - Lightly grit blasted the starboard side to eliminate any fine rust which formed or base metal left out overnight. Welded draft markings on the bow. 1:45 p.m., cleaned surface with toluene solvent. Temperature 24°C (75°F), humidity 70%.
Weather sunny and clear, some wind.
- June 5, 75 - Applied coating to starboard side and squeegeed excessive material to fill pits. Temperature 21°C (70°F), humidity 50%.
- June 6, 75 - Grit blasted port side.
- June 7, 75 - Grit blasted remaining port section. 1:45 p.m., cleaned starboard and port side with toluene. Had to reblast part of the port side. 3:45 p.m., primed port side. Temperature 18°C (65°F), humidity 64%. 7:10 p.m., applied topcoat and squeegeed port side.
- June 9, 75 - Grit blasted remaining port side. 2:00 p.m., ground off the top of the asperities on port side. Toluene cleaned remainder of areas where needed. 4:15 p.m., primed remainder of both sides. 7:20 p.m., applied urethane to remainder of port side.
Temperature 20°C (68°F), humidity 64%.
- June 10, 75 - 7:00 a.m., ground off asperities on port side. 8:15 a.m., cleaned port side. 9:20 a.m., started applying 250 mils to starboard section. Temperature 17°C (63°F), humidity 72%.
12:00 p.m., applied 100 mils to port section. Temperature 26°C (79°F), humidity 58%. 2:00 p.m., finished coating.
- June 11, 75 - 7:30 a.m., final touchup. 12:00 p.m., completed job.

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TABLE II-12

TABULATION OF THE BOND STRENGTH VALUES OBTAINED ON SPECIMENS COATED DURING THE APPLICATION OF THE NONSOLVENTED URETHANE COATING ON THE HULL OF THE USCG CUTTER MACKINAW

Specimen	Bond Strength Values Tension	Remarks
Port-Bow	1,485	Broke in the primer
Port 30 ft back from the bow	1,625	Broke in the primer
Port 60 ft back from the bow	1,525	Broke in the primer
Starboard-Bow	1,460	Broke at the metal
Starboard - 30 ft back from the bow	1,720	Broke in the primer
Starboard - 60 ft back from the bow	1,420	Broke in the primer

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TABLE II-13

TABULATION OF THE PROPERTIES OF THE NONSOLVENTED POLYURETHANE APPLIED TO THE
HULL OF THE USCG CUTTER MACKINAW

	Starboard	Port
Minimum average bond strength of primer	1,725 psi	1,925 psi
Minimum average bond strength of urethane	1,530 psi	1,545 psi
Final coating roughness	120 μ " CLA	120 μ " CLA
Coating thickness	250 mils-bow 30 mils back	100 mils-bow 30 mils back
Coating thickness-primer	5 to 10 mils	5 to 10 mils
Hardness (pencil)	E3*	E4*

* Coating indents with the E3 lead, will not scratch with any lead.

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10.6 USCG Cutter Raritan

The overall dimensions of the Cutter Raritan are:

110 ft long

27.3 ft beam

12.25 ft draft

380 tons maximum displacement - steel hull.

This ship is essentially the same as the Cutter Yankton and Sauk, all being icebreaking tugs.

During the month of July 1974, the Cutter Raritan was coated with a non-solvented polyurethane system manufactured by Xenex Corporation called Zebron.

The entire area below the water line was coated with between .030" and .040" of material with the thickness increasing to .100" at the bow.

The coating was applied over a "white metal" grit blast using spray equipment specifically manufactured for applying that material. This coating manufacturer also requires special applicators.

The coating conditions during application are shown in Table II-14.

After the coating was applied, some large bubbles formed on a section near the stern. It was determined that the substrate had become wet due to condensation from the floor of the dry dock. The damaged coating was removed to areas where the bond appeared tenuous. Repair was accomplished by applying a hand mix coating to the areas where the damage occurred.

Photographs of the Cutter Raritan during the coating are seen in Figure II-19.

A tabulation of the coating properties obtained during the application of the Raritan coating is shown in Table II-15.

During the month of March 1975, the hull of the Cutter Raritan was inspected while still in the water at St. Ignace, Michigan.

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TABLE II-14

COATING CONDITIONS FOR APPLICATION OF THE NONSOLVENTED URETHANE COATING TO THE
USCG CUTTER RARITAN

- June 26 - Grit blasted, primed and coated 25% of the hull (port stern section). Temperature 23°C (73°F), humidity 60%.
- June 27 - Grit blasted, primed and coated the rest of the port side (midship to bow). Temperature 24°C (75°F), humidity 60%.
- June 28 - Grit blasted, primed and coated starboard bow section.
Temperature 21°C (70°F), humidity 80%.
- June 29 - Grit blasted, primed and coated starboard bow section.
Temperature 20°C (68°F), humidity 80%.

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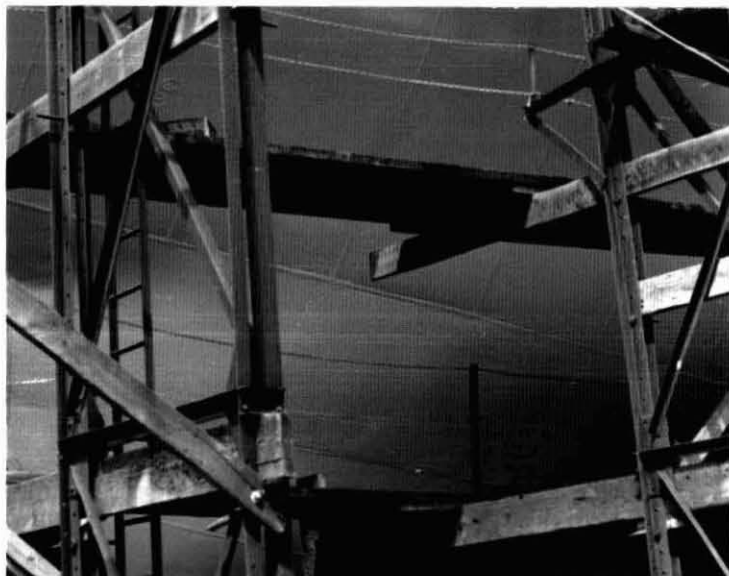


Figure II-19 Photographs of the Hull of the Cutter Raritan after Application of a Nonsolvent Polyurethane

TABLE II-15

TABULATION OF THE COATING PROPERTIES OBTAINED DURING THE APPLICATION TO THE
HULL OF THE USCG CUTTER RARITAN

Minimum average bond strength of the primer	900 psi
Minimum average bond strength of the polyurethane	1500 psi
Tensile strength of coating	2300 psi
Final surface roughness	220 μ "
Coating thickness primer	.005" to .001"
Coating thickness	.100" bow - .040" rest of hull
Hardness (pencil)	E3*

* Coating indented with the E3 lead, would not scratch with any lead.

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The ship had seen service assisting the Cutter Mackinaw at Sault St. Marie on the Great Lakes. At that time the coating appeared to be completely intact except for a 4" x 6" triangular shaped portion on the stern. Photographs of the ship taken during that inspection are shown in Figure II-20. The standard alkyd paint above the urethane was completely removed at the bow. Areas below the water line could not be seen because of the heavy ice, however during a period when the ship was in clear water, the hull was examined and found to show no damage as far down as could be seen.

The Cutter Raritan saw icebreaking service after that and was dry docked on August 11, 1975. At that time the hull was examined for damage.

Figure II-21 shows the condition of the ship's hull "as dry docked". The coating was essentially all intact below the water line except for very small isolated areas where the light rust spots could be seen. The upper portion near the water line had isolated areas near the bow where the coating was removed. Several areas approximately 1 sq ft were seen where the coating had either chipped or worn away. An estimated 98% of the coating was still visible on the hull.

Much of the coated area was covered with marine growth. The areas near the water line had a buildup of grass while below the water line, a jelly-like substance had formed. The dark areas seen in Figure II-21 are the jelly-like deposits.

The hull was cleaned with a water jet from a hydroblast unit. The water line was completely cleaned of the grass deposits and approximately 70% of the underhull was cleaned. Photographs showing the full extent of the damage after cleaning are seen in Figure II-22.

The bulk of the damage was at the bow stem and in isolated areas near the water line. Some of the damage was said to have been caused by hitting

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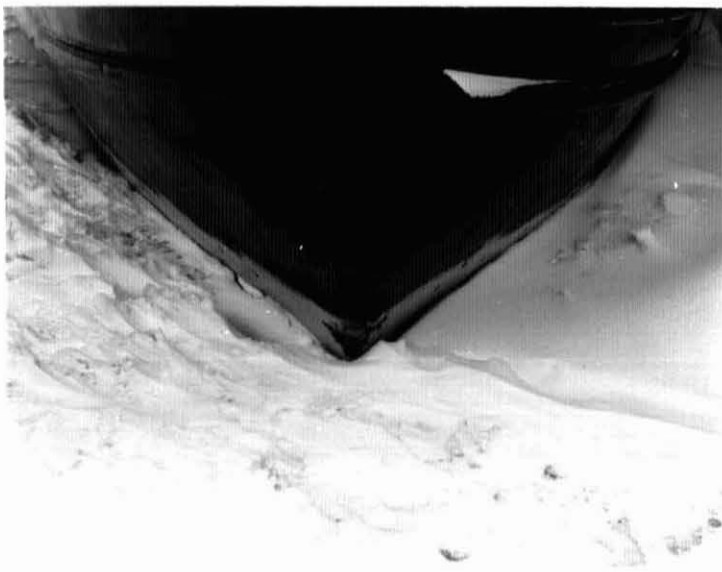


Figure II-20 Water Line Area of the Hull of the USCG Cutter Raritan after Icebreaking Service.
Photographs taken during March 75 before the end of the icebreaking season.

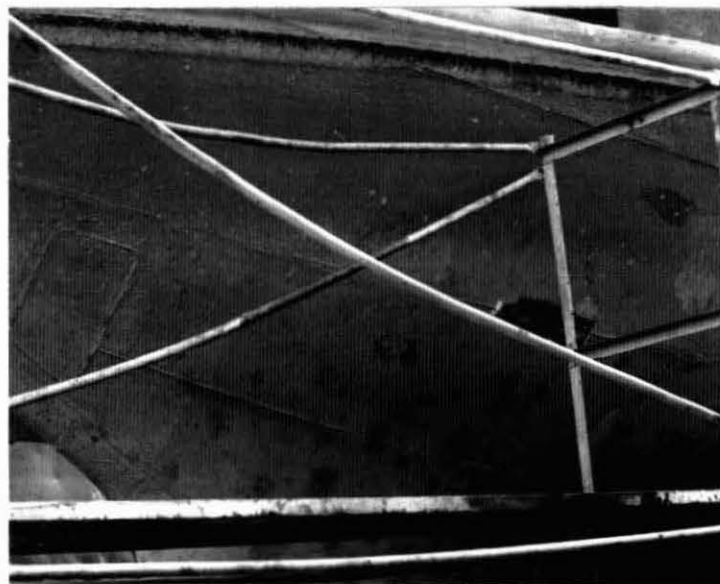


Figure II-21 Condition of Hull of the USCG Cutter Raritan before Cleaning

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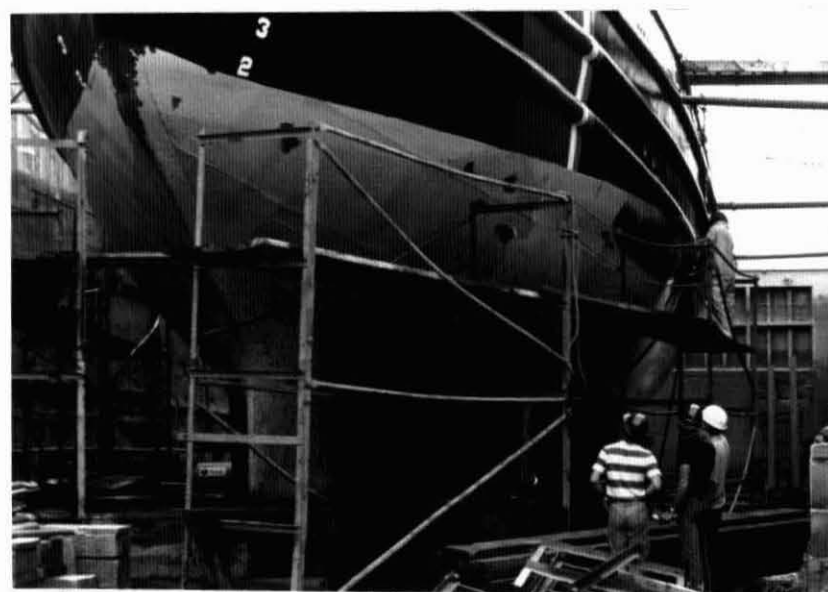
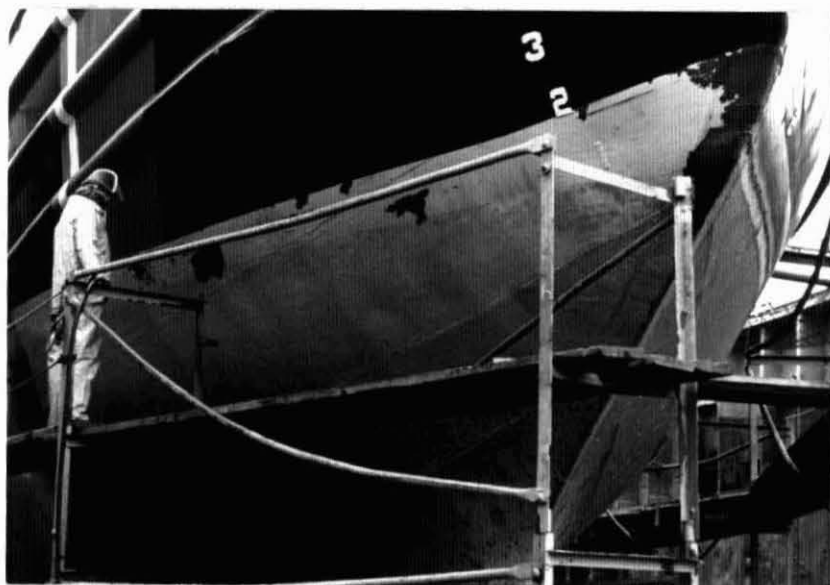
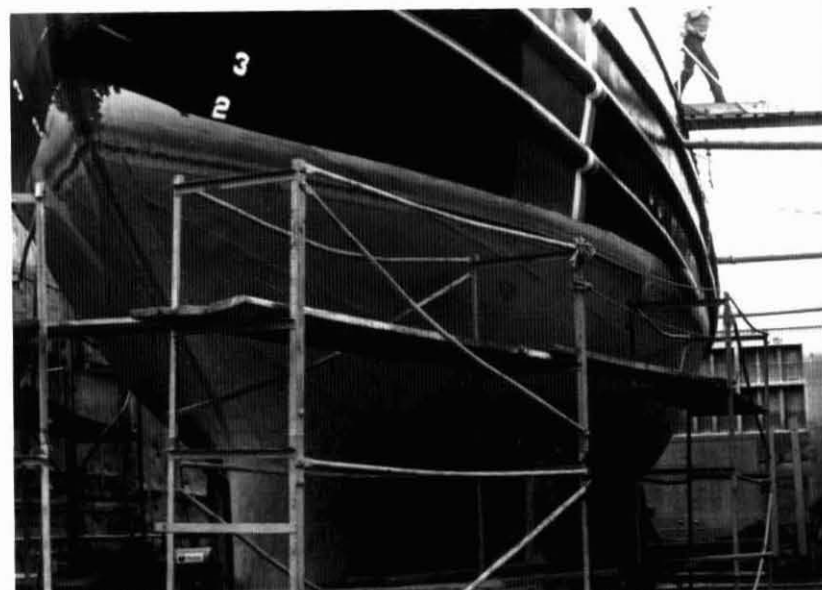
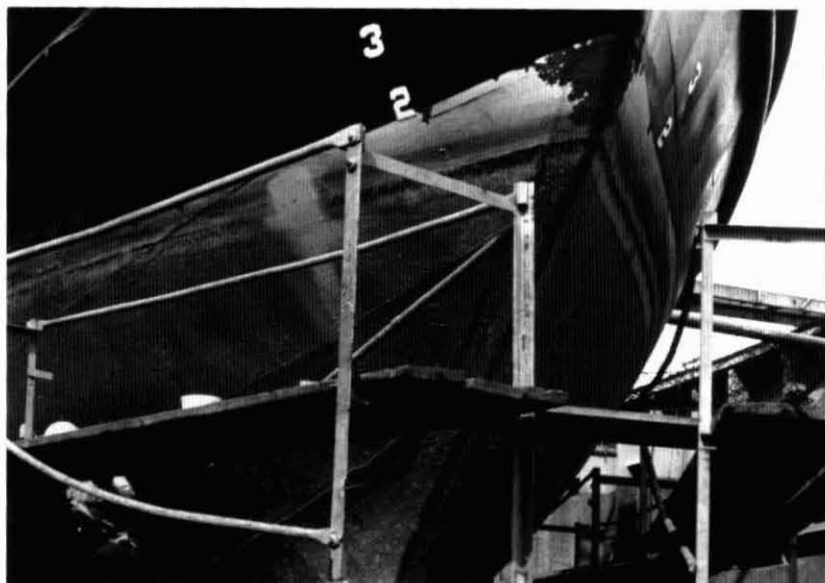


Figure II-22 Bow of the Cutter Raritan before (Top) and after (Lower) Cleaning by Hydroblasting

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foreign objects in the water. According to ships captain and crew, at least one of the chipped areas on the port side was said to have been caused by striking a foreign object in the water during icebreaking.

The ship saw icebreaking service throughout the winter in the Great Lakes. Over 600 hours of icebreaking was accomplished. The service seen was as follows:

January 20th to the 30th - broke ice in Northern Great Bay area for nine days. A total of 87.1 hours of icebreaking was logged. The heaviest ice seen was between 18" and 24". There were pressure ridges extending 6 to 8 ft above the water line. The ice seen in this area was not "hard blue" ice. Icebreaking was accomplished during most of this time with a ship's power requirement in the ninth step.

During March, the ship broke ice for 181.2 hours. A total of 1195.5 miles was logged with only 300 miles in open waters. Most of the ice broken was the brash ice but during this period hard blue ice was encountered. The ship was working between Sioux Saint Marie and St. Ignace during this period.

Other ships involved in the operation were

The USCG Cutter Mackinaw

The USCG Cutter Naugetuck

The USCG Cutter West Wind.

During April, 423 hours of icebreaking was accomplished. The vessel traveled 1450.7 miles with approximately 300 miles in open water.

Some indication of a reduction in power was seen after the ship had been coated. Normal running in brash ice is in the 9, 10 or 11 step. This year, the ship did most of the icebreaking in brash ice in the 7, 8 or 9th step.

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Before the coating was applied the ship's generator requirement was 1200 to 1300 amps in open water. After the coating had been applied the generator output was 900 amps to maintain the same speed. After a year of service, the amperage had increased to 1200 amps. It is very difficult to come to definite conclusions concerning the power change without instrumenting the ship to obtain hard data but indications are that there may be a reduction in power requirement as a result of a low friction coating.

In addition to the damaged areas there were isolated areas below the water line where the top layer of coating had separated from the bottom layer. This was determined to be a result of the application machine mismetering during the original coating application since some of the remaining bottom layer had not set up completely. There was a distinct difference in the color and texture of the bottom layer indicating an improper cure.

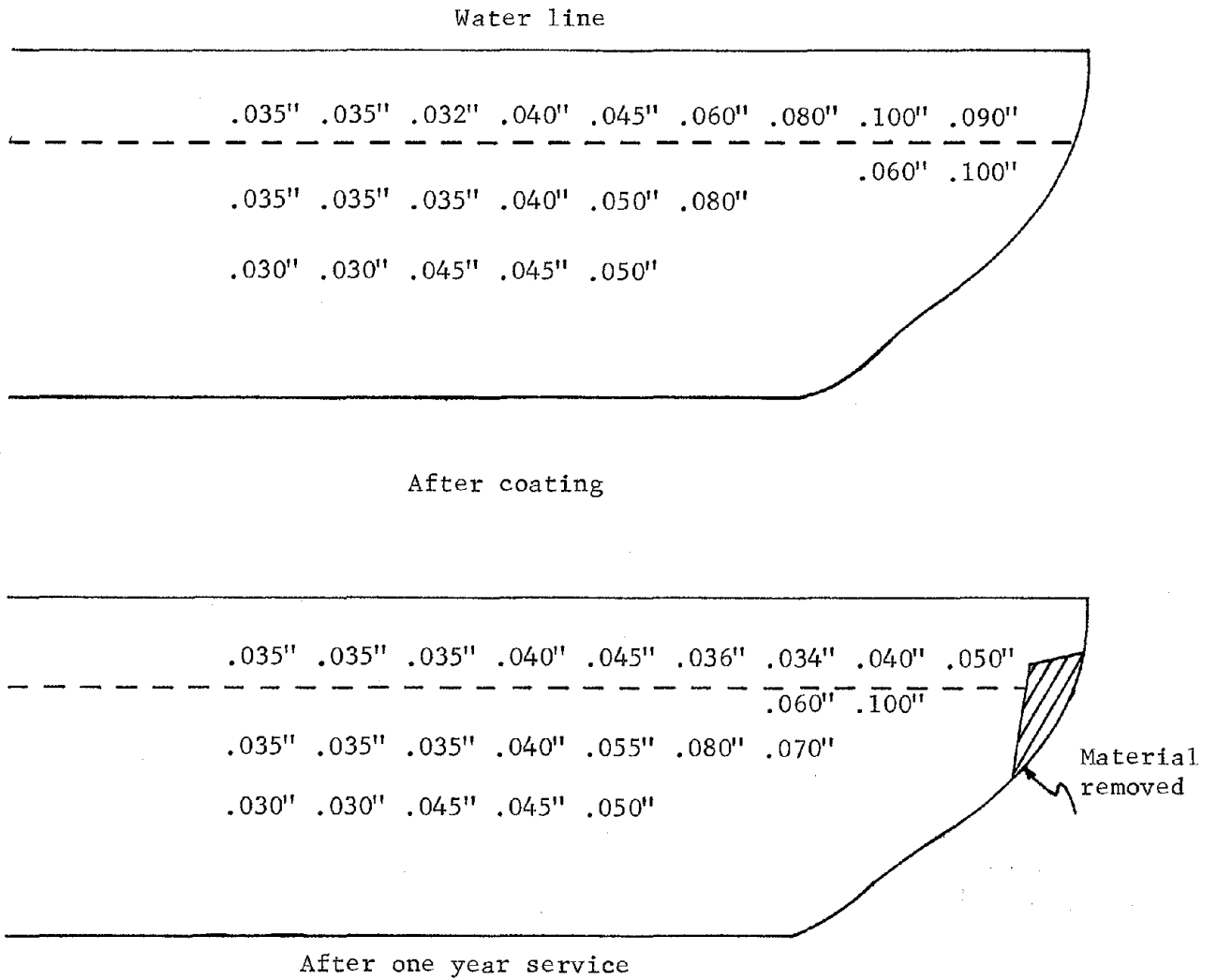
Thickness measurements were taken on the hull during the original coating and after one year of service. They are shown on the following page.

Wear occurred at the water line, near the bow, in a band approximately 8" wide. This could be seen by visual inspection. The worn areas were dull. Areas adjacent and on the underside of the hull were still shiny from the original coating glaze. The distribution of wear on both sides (port and starboard) appeared to be the same.

A comparison of the hull coating properties "as coated" and after one year of service are seen in Table II-16.

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Schematic of the Coating Thickness of the Nonsolvented Polyurethane on the USCG Cutter Raritan "as applied" and after One Year of Service

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TABLE II-16

COMPARISON OF XENEX CORPORATION NONSOLVENTED POLYURETHANE
BEFORE AND AFTER ICEBREAKING SERVICE
USCG CUTTER RARITAN

	Before Service	After Service
Average Thickness		
- Water line bow	.080 - .100"	.034 - .050"
- Water line - 30 ft from the bow	.035 - .045"	.022 - .040"
- Water line midship to stern	.035" - .040"	.030" - .038"
- Below Waterline	.035" - .045"	.035" - .045"
Average Surface Roughness		
- Water line	220 μ "	350 μ "
- Below water line	220 μ "	220 μ "
Hardness (Pencil)		
- Water line	E3*	E3*
- Below water line	E3*	E1

* Coating indented with the E3 lead would not scratch with any lead.

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10.6.1 Results

The evaluation gave very encouraging results since only isolated areas at the water line were damaged. Below the water line most of the coating was intact except small areas where the application machine had mismetered. After inspection and cleaning, repair was accomplished over a two-day period and the ship was put back in the water.

Some indication of a reduction in ship power required for both open water and icebreaking were noted by the ships captain and crew, indicating a reduction in resistance. This point is extremely important and should be studied by instrumenting the ship to determine the coating effect on resistance during full-scale testing.

10.6.2 Repair of Coating

All areas at the waterline and at the bow where damage or mismetering had occurred were repaired while in dry dock. The repair was accomplished by hand mixing the coating material and trowelling it on the surface after being cleaned, grit blasted and primed. In addition a three-foot section above the water line at the bow and tapering back to the water line was coated. This protects the upper bow against ice which slides against it, after it is broken and forced under the hull. The additional coating will also eliminate a coating edge in the bow area where the most severe damage occurs. The condition of the hull after grit blasting is seen in Figure II-23.

Bond strength test specimens were taken of the newly applied material during the coating application.

The bond strength measurements obtained were as follows:

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Figure II-23 Condition of the Hull of the Cutter Raritan after Grit Blasting the Damaged Areas for Repair

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Specimen No.	Stress (psi)	Remarks
1	1694	Failed in the fixturing epoxy
2	1567	Failed at the interface between the steel and primer
3	1618	Failed at the interface between the steel and primer
4	1541	Failed in the fixturing epoxy
5	1490	Failed at the interface between the steel and the primer
6	1503	Failed in the fixturing epoxy

The ship was put back into the water to see icebreaking service during the 75-76 icebreaking season.

10.6.3 Conclusions

The nonsolvented polyurethane applied the USCG Raritan gave the most promising results. After 600 hrs of icebreaking service, approximately 50 sq ft of damage was noted and repaired.

The coating showed little antifouling characteristics but the growth which was seen on the hull was removed by a hydroblast unit. No damage to the coating was noted after cleaning the hull.

The coating should be applied to a second icebreaker of the same size (110 ft icebreaking tug - WYTM) which is operating in salt water. The coating thickness should be .060" on the underside and .150" in areas of maximum wear. The maximum wear areas are:

- a) Bow from the first bumper to keel and continue 30 ft back from the stem.
- b) One foot above and 2 ft below the water line. The total length of the ship should be coated.

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The transition from .150" to .060" should be a gradual taper over approximately 2 ft. The line from the first bumper to the water line coating should be a gradual taper of approximately 30°. A schematic of the hull coating thickness is shown in the summary and conclusion portion of the report.

The black coating above the water line used for cosmetic reasons can be painted over the polyurethane to keep the color scheme the same.

10.7 USCG Cutter West Wind

The overall dimensions of the Cutter West Wind are

269 ft long

63.5 ft beam

29 ft draft

6500 tons displacement - steel hull.

The coating applied to the hull of the West Wind was the Baltimore Glass flake polyester. It is essentially a polyester matrix with glass flake particles dispersed throughout to reduce coating wear. The thickness applied was .035" to .040" dry.

The coating was applied at the Coast Guard yard at Baltimore and put into service in June 1974. The ship served in the Arctic for a short period of time and returned to the Great Lakes during the 74-75 icebreaking season in order to aid in keeping the shipping lanes open throughout the winter.

Approximately 700 hrs of icebreaking was logged throughout the season. The heaviest ice encountered was in the Great Lakes for the two and one-half months.

The ship was examined while in the water during August. Little could be determined at that time. Photographs of the hull were taken and are shown in Figures II-24 and II-25.

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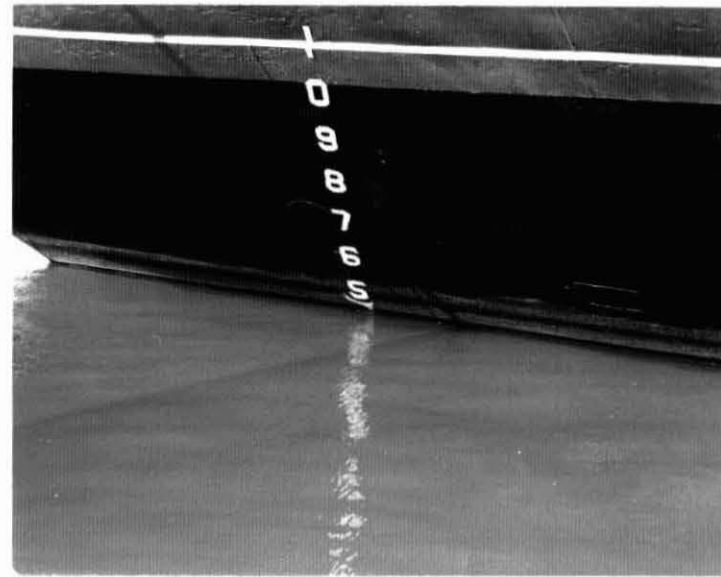
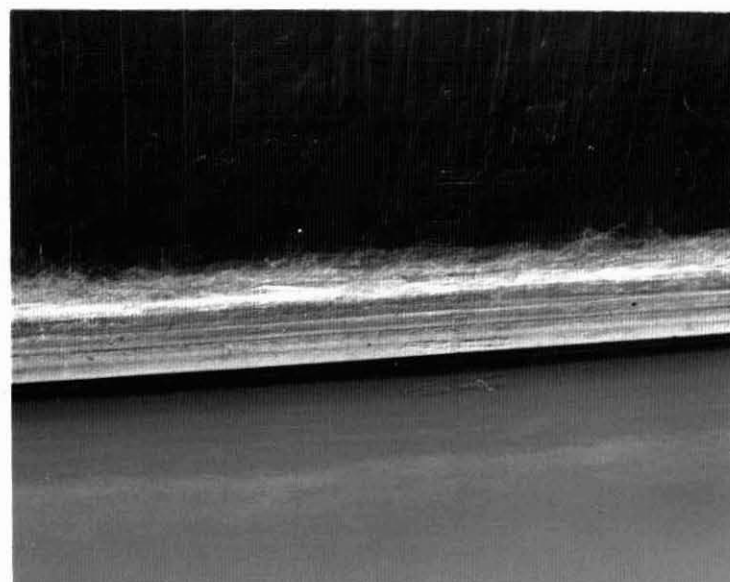
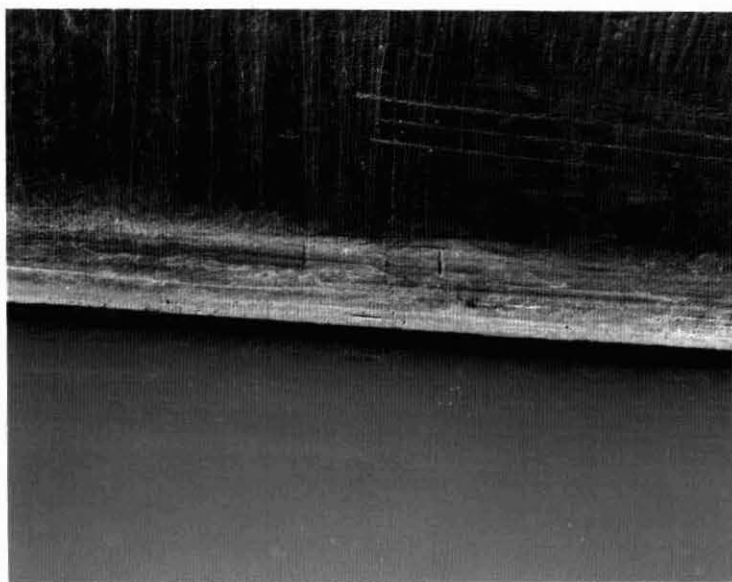


Figure II-24 Typical Appearance of the Polyester Glass Flake Coating at the Waterline on the Hull of the USCG Cutter Westwind (Midship to Stern)

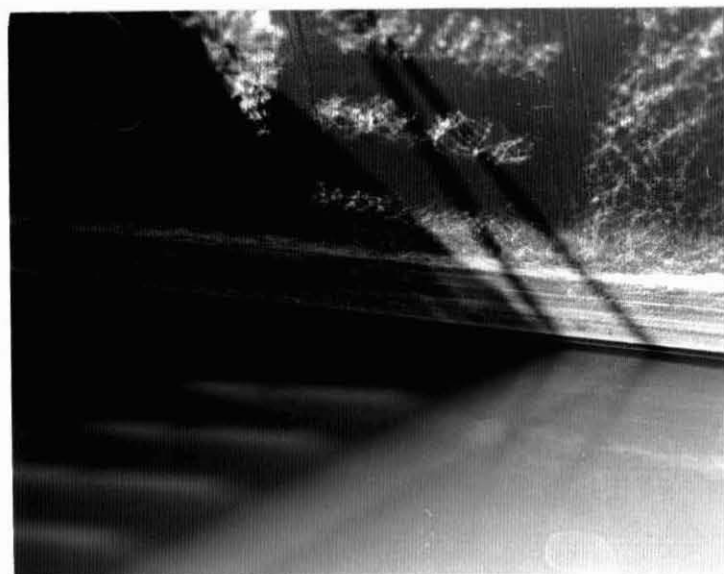


Figure II-25 Typical Appearance of the Polyester Glass Flake Coating at the Water Line on the Hull of the USCG Cutter Westwind (Bow to Midship)

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During November 1975, the ship was put into dry dock and the hull was examined. A photograph of the appearance of the bow portion of the hull is shown in Figure II-26. The remaining coating appears white and the steel hull (areas where wear occurred) appears dark. Fifty to sixty percent of the coating was removed from the bow. The remainder had worn down to thicknesses varying from .006" to .040" near the keel.

Approximately 4 ft of coating was removed at the water line on the port, bow. The worn area tapered back to a 3 ft wide band approximately 15 ft back from the bow to midship and tapered even less to the stern. Below that, the coating still intact appeared heavily rusted in areas where the water appears to have penetrated the polyester and attacked the steel hull. There were several isolated areas below the totally worn water line where the coating was removed.

The starboard side was very similar to the port except the bow area had a 9 ft wide band where the coating was removed. Complete removal in isolated areas and rust penetration was also evident. Photographs of several portions of the hull are shown in Figures II-27 and II-28. Figure II-27 shows the port side from the bow to midship and Figure II-28 shows the stern and areas on the underside of the hull.

Hardness measurements were taken on the remaining coating and found to be harder than any of the polyurethane or epoxy coatings previously tested. The coating would not scratch with any lead including E5.

A survey of the thickness of the remaining hull coating was taken to determine the maximum wear areas.

The results are shown in Figure II-29 a and b.

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Figure II-26 Condition of the Bow of the USCG Cutter West Wind after Icebreaking Service. The white areas are the glass flake polyester coating. The grey areas are the steel surface where the coating was removed.

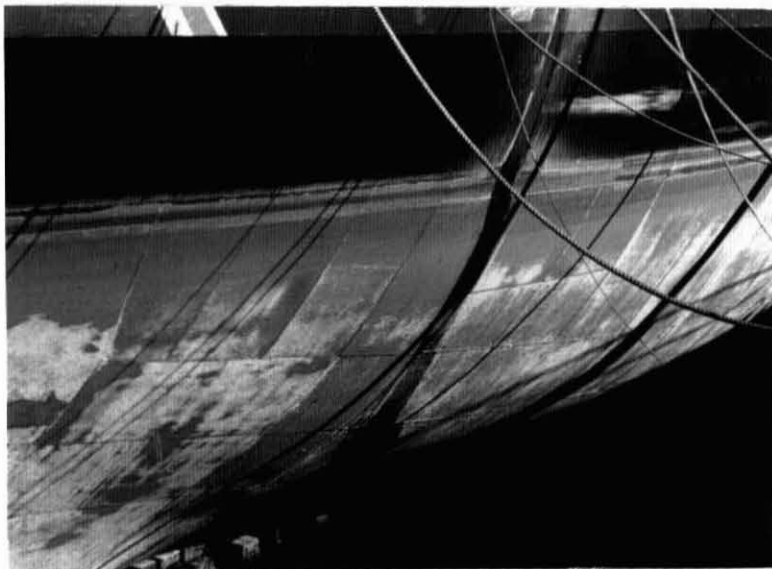


Figure II-27 Condition of the Hull of the USCG Cutter West Wind after Icebreaking Service.
Areas shown are from the bow to midship.

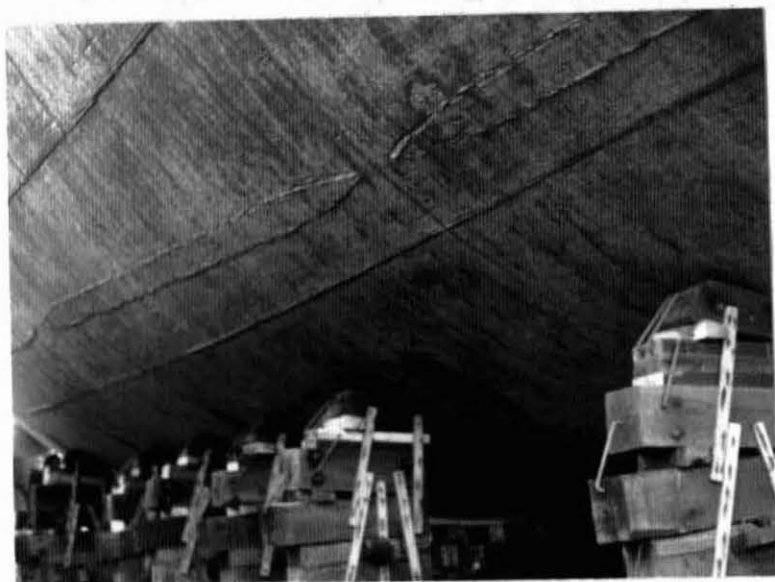
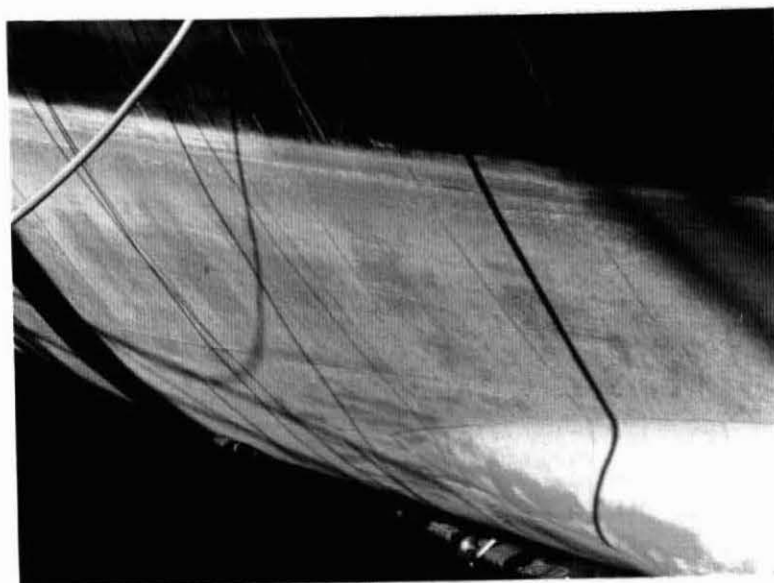


Figure II-28 Condition of the Hull of the USCG Cutter West Wind after Icebreaking Service.
Areas shown are the stern and underside portion of the hull.

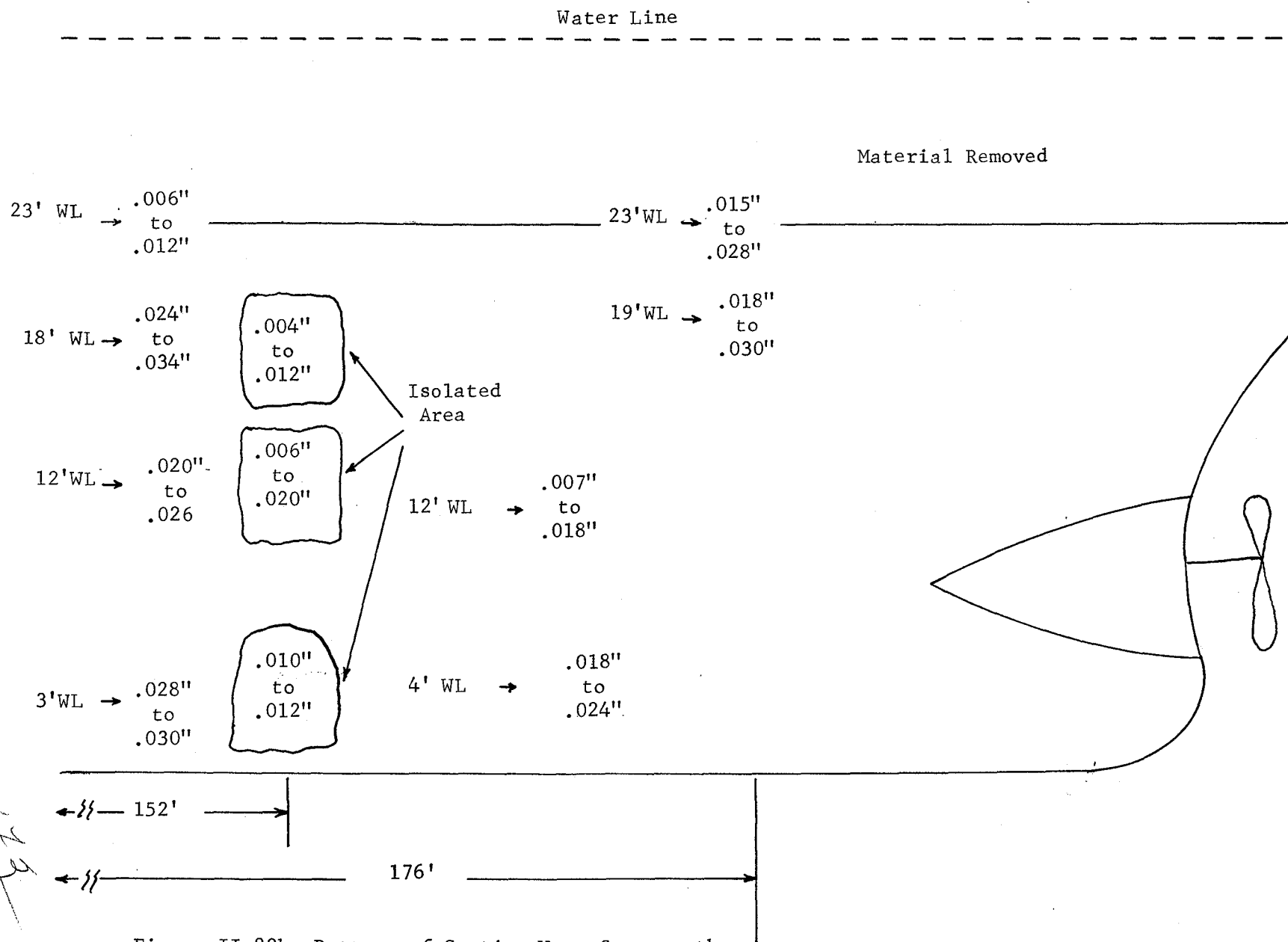


Figure II-29b Pattern of Coating Wear Seen on the USCGC West Wind after Service

SECTION 7

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